APPEAL BRIEF

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
Before the Board of Patent Appeals and Interferences

APPLICANT:	CALCEV ET AL	EXAMINER:	SOL
SERIAL NO.:	10/603,558	GROUP:	2619
FILED:	06/25/2003	CASE NO.:	CML01204M
TITLED:	METHOD AND APPARATUS FOR ROUTE DISCOVERY WITHIN A COMMUNICATION SYSTEM		

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November 13, 2007

**APPEAL BRIEF FOR APPELLANT
UNDER 37 C.F.R. §1.191**

Assistant Commissioner for Patents and Trademarks
Washington DC, 20231

1. REAL PARTY IN INTEREST

The real party in interest in this appeal is Motorola, Inc.

2. RELATED APPEALS AND INTERFERENCES

There are no other appeals or interferences that will directly affect, or be directly affected by, or have a bearing on the Board's decision in this appeal.

3. STATUS OF CLAIMS

This is an appeal from the final rejection mailed 10 October 2007. Claims 1-6, 9, 10, and 13-18 are the appealed claims. Claims 6-8, 10, 11, 17, and 18 were rejected under 35 U.S.C. 102(e) as being anticipated by U.S. Patent No. 6,704,293 B1 ("Larsson"). Claims 1-5, 9, 12-13, 15 and 16 were rejected under 35 U.S.C. 103(a) as being unpatentable over U.S. Patent No. 6,704,293 B1 ("Larsson") in view of U.S. Patent No. 6,304,556 B1 ("Haas").The claims are reproduced below in APPENDIX 1.

4. STATUS OF AMENDMENTS

No amendments have been filed subsequent to this Appeal.

5. SUMMARY OF CLAIMED SUBJECT MATTER

In order for one node within an ad-hoc communication system to communicate with another node in the ad-hoc communication system, a route must be "discovered" between the two nodes. This route will typically pass through intervening nodes that will relay the communications between the two nodes. During prior-art route discovery, a message flooding procedure occurs that is often the basis of on-demand route discovery and network initialization. Message flooding is basically defined as a broadcast procedure covering a complete network. It operates as follows: When a node, or remote unit, in a network wishes to discover a route to another node in the network a message is broadcasted to all of its neighbors specifying the destination address. Upon receiving the message, all of the neighboring nodes will rebroadcast the message to their neighbors. When a node receives the same message again, it discards it. The procedure repeats itself until all of the nodes in the network are reached, or a time-to-live for the message expires. As discussed, the purpose to flood the network in a routing algorithm is

essentially to find a path to send data to destinations. The message content is usually a request of route discovery.

Although message flooding is a dependable way to find a route within the network, flooding is proven to generate excessive amounts of system traffic and interference. To address this issue, the present invention provides for an ***overlay*** communication system that aides in determining a route between nodes in an ***underlay*** communication system. In particular, when a first node wishes to discover a route to a second node, the first node notifies an overlay communication system, which notifies all nodes in the underlay communication system of the desire. Both the first and the second nodes begin flooding the underlay system simultaneously. When a node in the underlay system hears both the flood messages from the first and the second node, the overlay communication system is notified and stops all flooding. The route information is then provided to the first and the second nodes via the overlay communication system.

Because flooding takes place simultaneously from two nodes within the underlay communication system, the search will reduce the amount of signaling in half for a uniform distribution of the ad hoc nodes. This will equate into a less interference in the ad hoc network and less battery drain. A second advantage of the disclosure is the reduction of discovery time. If the search is unidirectional the expected time to discover the route is the time that a flood message reaches the target plus the time that the acknowledgement reaches the source. In the preferred embodiment of the present invention this time is cut in half since the message and the acknowledgement have to parse half of nodes than in the actual algorithms.

In claim 1, a method for route discovery is provided. The method comprises the steps of:

- determining that a first node needs to communicate with a second node (Page 8, lines 20-21), wherein the first and the second nodes are part of an underlay communication system (FIG. 1);
- sending, by the first node, a message to an overlay communication system notifying the overlay communication system of the need to communicate with the second node (Page 10, lines 21-24);
- receiving by the first node, from the overlay communication system, instructions to broadcast a route-discovery message (Page 10, lines 24-26);
- broadcasting the route discovery message within the underlay communication system (Page 10, lines 27-29); and
- receiving by the first node route information from the overlay communication system (Page 10, lines 31 to Page 11, line 1).

Claim 4 recites a method comprising the steps

- receiving, by a first node, from an overlay communication system, a message instructing the first node to broadcast a route discovery message (Page 9, lines 18-19), wherein the first node exists within an underlay communication system (FIG. 1); and
- broadcasting the route discovery message within the underlay communication system (Page 9, lines 20-21).

Claim 6 recites a method for operating a node within an underlay communication system. The method comprises the steps of:

- receiving a route-discovery message from a first node, wherein the first node is part of an underlay communication system (Page 11, lines 9-10);
- receiving a route-discovery message from a second node, wherein the second node is part of the underlay communication system (Page 11, lines 10-11);
- determining route information based on the route-discovery messages (Page 11, lines 16-17); and
- transmitting the route information through an overlay communication system to the first node (Page 11, lines 18-19).

Claim 10 recites a method comprising the steps of:

- receiving at a base station in an overlay communication system, a message from a first node in an underlay communication system, the message indicating a need to discover a route to a second node (Page 12, lines 3-6);
- broadcasting by the base station, a message to nodes within the underlay communication system, the message instructing the nodes to monitor for flood messages from the first and the second nodes (Page 12, lines 6-8);
- receiving by the base station a message from a third node in an underlay communication system, the message comprising route information (Page 12, lines 12-13); and
- transmitting by the base station, the route information to the first node (Page 12, lines 14-15).

Claim 15 provides for an apparatus comprising:

- means (logic circuitry 701) for determining that a first node needs to communicate with a second node(Page 8, lines 20-21), wherein the first and the second nodes are part of an underlay communication system (FIG. 1);
- means for sending (transmitter 703), by the first node, a message to an overlay communication system notifying the overlay communication system of the need to communicate with the second node (Page 10, lines 21-24);

- means for receiving (receiver 702) by the first node, from the overlay communication system, instructions to broadcast a route-discovery message (Page 10, lines 24-26);
- means for broadcasting (transmitter 703) by the first node, the route discovery message (Page 10, lines 27-29); and
- means for receiving (receiver 702) by the first node route information from the overlay communication system (Page 10, lines 31 to Page 11, line 1).

Claim 16 provides for an apparatus comprising:

- means for receiving (receiver 702) by a first node, from an overlay communication system, a message instructing the first node to broadcast a route discovery message (Page 9, lines 18-19), wherein the first node exists within an underlay communication system (FIG. 1); and
- means for broadcasting (transmitter 703) the route discovery message within the underlay communication system (Page 9, lines 20-21).

Claim 17 provides for an apparatus comprising:

- means for receiving (receiver 702) a route-discovery message from a first node, wherein the first node is part of an underlay communication system (Page 11, lines 9-10);
- means for receiving (receiver 702) a route-discovery message from a second node, wherein the second node is part of the underlay communication system (Page 11, lines 10-11);
- means for determining (logic circuitry 701) route information based on the route-discovery messages(Page 11, lines 16-17); and
- means for transmitting (transmitter 703) the route information through an overlay communication system to the first and the second nodes (Page 11, lines 18-19).

Finally, claim 18 provided for an apparatus comprising:

- means for receiving (receiver 702) at a base station in an overlay communication system, a message from a first node in an underlay communication system, the message indicating a need to discover a route to a second node (Page 12, lines 3-6);
- means for broadcasting (transmitter 703) by the base station, a message to nodes within the underlay communication system, the message instructing the nodes to monitor for flood messages from the first and the second nodes (Page 12, lines 6-8);

- means for receiving (receiver 702) by the base station a message from a third node in an underlay communication system, the message comprising route information (Page 12, lines 12-13); and
- means for transmitting (transmitter 703) by the base station the route information to the first node (Page 12, lines 14-15).

6. GROUNDS OF REJECTION TO BE REVIEWED ON APPEAL

The grounds of rejection to be reviewed on appeal will be:

- The rejection of claims 6-8, 10, 11, 17, and 18 under 35 U.S.C. 102(e) as being anticipated by U.S. Patent No. 6,704,293 B1 ("Larsson"); and
- The rejection of claims 1-5, 9, 12-13, 15 and 16 under 35 U.S.C. 103(a) as being unpatentable over U.S. Patent No. 6,704,293 B1 ("Larsson") in view of U.S. Patent No. 6,304,556 B1 ("Haas").

7. ARGUMENT

(i) *Rejections under 35 USC 112 first paragraph:*

None

(ii) *Rejections under 35 USC 112, second paragraph:*

None

(iii) *Rejections under 35 USC §102:*

Claims 6-8, 10, 11, 17, and 18 were rejected under 35 U.S.C. 102(e) as being anticipated by U.S. Patent No. 6,704,293 B1 ("Larsson").

The present invention provides for an ***overlay*** communication system that aides in determining a route between nodes in an underlay communication system. Claims 6-8, 10, 11, 17, and 18 all contain limitations using the term "***overlay*** communication system". In rejecting claims 6-8, 10, 11, 17, and 18, Examiner Sol fails to give "overlay

communication system" its plain meaning as known in the art, and is reading the term in a vacuum.

Analysis of Larsson reveals that Larsson teaches route discovery ***within a single communication system.*** Particularly, Larsson reveals a method to piggyback broadcast messages together to reduce the overhead and the broadcast traffic. In rejecting the Applicants' claims, Examiner Sol states that the ad-hoc network as disclosed by Larsson meets the limitation of the claimed underlay communication system (Page 3) and that the ***network adaptation layer*** meets the limitation of an ***overlay communication system*** as claimed (Page 4). It is inconceivable to the Applicants how a network adaptation layer can possibly be equated to a communication system. In equating a network adaptation layer with an overlay communication system, Examiner Sol fails to give the term "overlay communication system" its plain meaning as known in the art, and is reading the term in a vacuum.

Words of a Claim Must be Given Their Plain Meaning Unless They are Defined in the Specification

As stated in MPEP 2111.01, the words of a claim must be given their plain meaning unless they are defined in the specification. When not defined within the specification, MPEP 2111.01 states that the words of the claim "must be read as they would be interpreted ***by those of ordinary skill in the art***". (MPEP 2111.01, emphasis added). As stated in MPEP 2111.01, "[t]his means that the words of the claim must be given their plain meaning unless applicant has provided a clear definition in the specification."

In this case, the ordinary meaning of claim language as understood by a person of skill in the art may be readily apparent even to lay persons. Claim construction in these cases involves little more than the application of the ***widely accepted meaning of commonly understood words***. See Brown v. 3M, 265 F.3d 1349, 1352 (Fed Cir. 2001) (holding that the claims did "not require elaborate interpretation").

The term overlay and underlay communication system is a term that is extremely common in the art, with literally dozens of US patents and IEEE publications using the term exactly how it is meant by the Applicants. More particularly, those skilled in the art will without a doubt recognize an "overlay communication system" to be a wireless communication system that overlaps in space and some times in frequency with the underlay wireless system. Some publications utilizing the term "overlay", which is emphasized, are reproduced below:

This technique uses a 10 MHz Broadband- CDMA (B-CDMA) signal which spreads over the entire contiguous bands A or B, leaving the extended bands for AMPS alone. The B-CDMA ***Overlay*** does not require displacing any AMPS users. Instead it uses a combination of broadband DS-SS along with agile receive and transmit notch filtering at the base station to cohabitate the same spectrum used by the AMPS service. By this technique, a significant increase in capacity can be realized. The capacity of broadband CDMA overlaying a GSM cellular system. Grieco, D.M.; Schilling, D.L.; Vehicular Technology Conference, 1994 IEEE 44th 8-10 June 1994 Page(s):31 - 35 vol.1.

"One possible way to make this transition is to employ CDMA ***overlay***, in which a CDMA cellular system would be implemented in a frequency band which is dedicated to a narrowband cellular system". Multicarrier CDMA for cellular overlay systems, Rainbolt, B.J.; Miller, S.L.; Selected Areas in Communications, IEEE Journal on Volume 17, Issue 10, Oct. 1999 Page(s):1807 – 1814.

With the expected wireless revolution in telecommunications, the available spectrum should be used efficiently and flexibly. One step in this direction is the use of SS ***overlay***. Spectrum spreading allows overlaying signals on frequency bands which are already occupied by narrow-band users without influencing these in a considerable way . . . . "A CDMA overlay system using frequency-diversity spread spectrum" Papproth, E.; Kawas Kaleh, G.; Vehicular Technology, IEEE Transactions on Volume 48, Issue 2, March 1999 Page(s):397 – 404.

In this paper, we design a system with an ad hoc ***overlay*** network, which we denote as the secondary system (SEC), to efficiently utilize the bandwidth left unused in a cellular system, which we denote as the primary system (PRI). Enhancing wireless spectrum utilization with a cellular-ad hoc overlay architecture Sankaranarayanan, S.; Papadimitratos, P.; Mishra, A.; Military Communications Conference, 2005. MILCOM 2005. IEEE 17-20 Oct. 2005 Page(s):405 - 412 Vol. 1

A multiple mode, personal, wireless communications system is disclosed which exists within a radiotelephone network serving general customers and provides

unique additional services to a select group of customers equipped with special handsets, without impacting the general customers. The special handsets automatically switch between and operate in either analog or digital mode with the standard radiotelephone network and in an enhanced cordless mode when within range of independent pico cells, that are interconnected with the public switched telephone network. Each of the network transparent pico cells is controlled via a framework of ***overlay*** cells that operate independently of the radiotelephone network and use a unique control protocol on a relatively small number of reserved channels, with a use hierarchy that is reversed with respect to standard radiotelephone channels. US6526277 B1

A cellular communication system has a frequency bandwidth arranged into a plurality of frequency channels, and a plurality of neighbouring first (130) and second (132) sites each having sectors (a1-f1, a2-f2) containing at least one frequency channel. Corresponding sectors in each of the neighbouring first (130) and second sites (132) have consecutive frequency channels from the frequency bandwidth, thereby producing a two-site re-use pattern (134, 136). The cellular communication system may be adapted to support an underlay/***overlay*** cell configuration in which neighbouring first (230) and second (232) sites each have six-sectors containing at least one frequency channel (b1-b12) of a two-site repeat pattern. The six sectors further each contain at least one frequency channel (t1-t6) of a one-site repeat pattern. Corresponding sectors in each of the neighbouring first (130) and second sites (132) have consecutive frequency channels in the two-site repeat pattern and identical channels in the one-side repeat pattern. EP867100B

Therefore, because the term "overlay communication system" must be given its plain meaning, and because the term "overlay communication system" is readily apparent (even to lay persons), claim construction involves little more than the application of the widely accepted meaning of "overlay communication system" to the claim. Therefore, Examiner Sol's equating a network adaptation layer to a communication system is improper.

Claims are not to be Read in a Vacuum, and Limitations Therein are to be Interpreted in Light of the Specification

The person of ordinary skill in the art is deemed to read the claim term not only in the context of the particular claim in which the disputed term appears, but in the context of the entire patent, including the specification. The court explained that point well in Multiform Desiccants, Inc. v. Medzam, Ltd., 133 F.3d 1473, 1477 (Fed. Cir. 1998). See also Medrad, Inc. v. MRI Devices Corp., 401 F.3d 1313, 1319 (Fed. Cir. 2005) ("We cannot look at the ordinary meaning of the term . . . in a vacuum. Rather, we must look at the ordinary meaning in the context of the written description and the prosecution history.")

Clearly, the Applicants' specification and drawing support the above-defined meaning of the term "overlay communication system" since two communication systems are clearly defined in FIG. 1, and every use of the term "overlay communication system" conforms with the commonly-held meaning of the term. Therefore claim construction involves little more than the application of the widely accepted meaning of "overlay communication system" to the claim.

<u>When the term "Overlay Communication System" is Not Read in a Vacuum, and Given its Plain Meaning, Claims 6-8, 10, 11, 17, and 18 are not Anticipated by Larsson.</u>

When the term "overlay communication system" is not read in a vacuum, and given its plain meaning, claims 6-8, 10, 11, 17, and 18 are not anticipated by Larsson. Analysis of Larsson reveals that this reference teaches a method to piggyback broadcast messages together to reduce the overhead and the broadcast traffic. Larsson fails to teach or otherwise suggest that an overlay communication system can be used by nodes in an underlay communication system to transmit route information. In fact, the term ***<u>overlay or underlay aren't even mentioned by Larsson.</u>*** Because of this, claims 6-8, 10, 11, 17, and 18 are in proper condition for allowance.

(iv) *Rejections under 35 USC §103(a):*

Claims 1-5, 9, 12-13, 15 and 16 are rejected under 35 U.S.C. 103(a) as being unpatentable over U.S. Patent No. 6,704,293 B1 ("Larsson") in view of U.S. Patent No. 6,304,556 B1 ("Haas"). These claims include the limitations that an overlay communication system aids an underlay communication system in route discovery. Here again Examiner Sol states that the network adaptation layer of Larsson meets the limitation of an overlay communication system as claimed. Again, it is inconceivable to the Applicants how a network adaptation layer can possibly be equated to a communication system. For the reasons stated above, Examiner Sol fails to give the term "overlay communication system" its plain meaning, and is reading the term in a vacuum.

When the term "overlay communication system" is not read in a vacuum, and given its plain meaning, claims 1-5, 9, 12-13, 15 and 16 are not made obvious by the combination of Larsson and Haas. In particular, claims 1 and 15 specifically state that the first and the second nodes are part of an underlay ad-hoc communication system, and that route information is received from an overlay communication system. As stated above, when the term "overlay communication system" is not read in a vacuum, and given its plain meaning, Larsson fails to teach or otherwise suggest that an overlay communication system can aide an underlay communication system with route discovery. Additionally, Haas fails to teach or otherwise suggest this limitation as well. Because of this, claims 1and 15 are allowable over the prior art of record.

Regarding independent claims 4 and 16, these claims specifically have the limitation that a node in an underlay communication system receives a message from an overlay communication system to begin broadcasting route discovery messages within the underlay communication system. As discussed above, Larsson teaches a method to piggyback broadcast messages together to reduce the overhead and the broadcast traffic. The Examiner states that Haas teaches a cellular communication system, however, the only discussion about cellular systems is the fact that ad hoc networks are different than cellular networks since there are no centralized entities in an ad hoc network (col. 2). Therefore, there is no disclosure from Larson or Haas of receiving from an overlay communication system instruction to broadcast a route discovery message.

Regarding all other claims, since these claims depend from allowable base claims, all other claims are in proper condition for allowance.

(i) *Further Rejections:*

None

CONCLUSION

In summary, all claims have the term "overlay communication system". This feature is neither taught nor suggested by the prior art. Examiner Sol refuses to give this term its plain meaning as known in the art, and is reading the term in a vacuum, stating that the network adaptation layer of Larsson meets the limitation of an overlay communication system as claimed. The Applicants point out that it is a mistake for Examiner Sol to read the term in a vacuum and not give this term its plain meaning as known in the art. The courts have consistently held that:

- words of a claim must be given their plain meaning unless they are defined in the specification;
- the claims are not to be read in a vacuum; and
- limitations therein are to be interpreted in light of the specification.

Because of this, Examiner Sol must interpret "overlay communication system" as it is meant to be interpreted in the Applicants specification. Once the proper definition for "overlay communication" is taken into consideration, it is clear that all claims are allowable over the prior art of record.

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CLAIMS APPENDIX

S/N 10/603,558
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1. (Previously Amended) A method for route discovery, the method comprising the steps of:

determining that a first node needs to communicate with a second node, wherein the first and the second nodes are part of an underlay ad-hoc communication system;

sending, by the first node, a message to an overlay communication system notifying the overlay communication system of the need to communicate with the second node;

receiving by the first node, from the overlay communication system, instructions to broadcast a route-discovery message;

broadcasting the route discovery message within the underlay communication system; and

receiving by the first node route information from the overlay communication system.

2. (Original) The method of claim 1 wherein the step of sending the message to the overlay communication system comprises the step of sending the message to a cellular communication system.

3. (Original) The method of claim 1 wherein the step of receiving route information comprises the step of receiving a sequenced list of IP addresses.

4. (Previously Amended) A method comprising the steps of:

receiving, by a first node, from an overlay communication system, a message instructing the first node to broadcast a route discovery message, wherein the first node exists within an underlay communication system; and

broadcasting the route discovery message within the underlay communication system.

5. (Original) The method of claim 4 wherein the step of receiving from the overlay communication system comprises the step of receiving from a cellular communication system.

6. (Previously Amended) A method for operating a node within an underlay communication system, the method comprising the steps of:

receiving a route-discovery message from a first node, wherein the first node is part of an underlay communication system;

receiving a route-discovery message from a second node, wherein the second node is part of the underlay communication system;

determining route information based on the route-discovery messages; and

transmitting the route information through an overlay communication system to the first node.

7. (Cancelled).

8. (Cancelled).

9. (Original) The method of claim 6 wherein the step of transmitting the route information comprises the step of transmitting the route information through an overlay cellular communication system.

10. (Previously Amended) A method comprising the steps of:

receiving at a base station in an overlay communication system, a message from a first node in an underlay communication system, the message indicating a need to discover a route to a second node;

broadcasting by the base station, a message to nodes within the underlay communication system, the message instructing the nodes to monitor for flood messages from the first and the second nodes;

receiving by the base station a message from a third node in an underlay communication system, the message comprising route information; and

transmitting by the base station, the route information to the first node.

11. (Cancelled)

12. (Cancelled).

13. (Original) The method of claim 10 wherein the step of receiving the route information from the third node comprises the step of receiving a sequenced list of IP addresses from the third node.

14. (Previously Amended) The method of claim 10 further comprising the step of transmitting by the base station, a flood stop message causing nodes within the underlay communication system to cease transmission of flood messages.

15. (Previously Amended) An apparatus comprising:

means for determining that a first node needs to communicate with a second node, wherein the first and the second nodes are part of an underlay communication system;

means for sending, by the first node, a message to an overlay communication system notifying the overlay communication system of the need to communicate with the second node;

means for receiving by the first node, from the overlay communication system, instructions to broadcast a route-discovery message;

means for broadcasting by the first node, the route discovery message; and

means for receiving by the first node route information from the overlay communication system.

16. (Previously Amended) An apparatus comprising:

means for receiving, by a first node, from an overlay communication system, a message instructing the first node to broadcast a route discovery message, wherein the first node exists within an underlay communication system; and

means for broadcasting the route discovery message within the underlay communication system.

17. (Previously Amended) An apparatus comprising:

means for receiving a route-discovery message from a first node, wherein the first node is part of an underlay communication system;

means for receiving a route-discovery message from a second node, wherein the second node is part of the underlay communication system;

means for determining route information based on the route-discovery messages; and

means for transmitting the route information through an overlay communication system to the first and the second nodes.

18. (Previously Amended) An apparatus comprising:

means for receiving at a base station in an overlay communication system, a message from a first node in an underlay communication system, the message indicating a need to discover a route to a second node;

means for broadcasting by the base station, a message to nodes within the underlay communication system, the message instructing the nodes to monitor for flood messages from the first and the second nodes;

means for receiving by the base station a message from a third node in an underlay communication system, the message comprising route information; and

means for transmitting by the base station the route information to the first node.

RELATED PROCEEDINGS

None

EVIDENCE APPENDIX

ENHANCING WIRELESS SPECTRUM UTILIZATION WITH A CELLULAR-AD HOC OVERLAY ARCHITECTURE

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ABSTRACT

The spectrum of deployed wireless cellular communication systems is found to be under-utilized, even though licensed spectrum is at a premium. In this paper, we design a system with an ad hoc overlay network, which we denote as the secondary system (SEC), to efficiently utilize the bandwidth left unused in a cellular system, which we denote as the primary system (PRI). The basic design principle is that the SEC operates in a non-intrusive manner and does not interact with the PRI. We develop the AS-MAC, an Ad hoc SEC Medium Access Control protocol to enable the interoperation of the PRI-SEC system. We address a number of technical challenges pertinent to this networking environment, and investigate a number of AS-MAC variants. Our performance evaluation results indicate that AS-MAC can transparently utilize up to 80% bandwidth left unused by the PRI.

INTRODUCTION

There is a strong belief that the spectrum both in the public as well as private sector in the United States is getting scarce. Recent measurements for cellular systems in major metropolitan areas ([1], [2]) suggest that spectrum utilization in several frequency bands is very low for extended periods of time. This means that the primary cause of spectrum scarcity is its inefficient utilization, rather than the unavailability of resources. It also suggests that adoption of efficient modulation and coding techniques, which can clearly improve spectrum utilization, cannot alone address the inefficiency.

A promising approach, known as spectrum sharing or pooling [3], is to enable two systems accessing the same spectrum. The owner of the spectrum, which we denote as the *primary system* (*PRI*), can allow a *secondary system* (*SEC*) to operate in the same spectrum, under the assumption that *SEC* utilizes only the portion of the spectrum left unused by the *PRI*. One example of such a scenario is that of a cellular provider leasing its unused spectrum to a *SEC* when the cellular traffic is expected to be significantly lower, e.g., between 9PM and 7AM. The *SEC* could, for example, utilize the unused resources to offer wireless Internet access services for home users.

In this paper, we consider the design of a *SEC* system overlaid on a *PRI* cellular system. In particular, we assume that that the *PRI* is a *TDMA/FDMA* based *GSM* cellular network [14]. The *SEC* is a multi-hop ad hoc network, which we denote as the *Ad hoc Secondary Network* (*ASN*). The fundamental constraints that *ASN* has to respect are (*i*) the *ASN* operate only over the resources (i.e., bandwidth) left unutilized by the *PRI GSM*, (*ii*) the operation of the *ASN* leads to no performance degradation of the *PRI*, and (*iii*) there is no exchange of signaling information between the *PRI* and the *ASN*.

To enable such an approach, we propose here the *Ad hoc SEC Medium Access Control* (*AS-MAC*) protocol, which is responsible for the following basic tasks. First, it detects the frequency bands utilized by the entities of the *PRI*, i.e., base station (*BS*) and the mobile stations (*MS*'s). Then, *AS-MAC* detects and maintains a picture of the (portion of) *PRI* resources that remain unutilized. Finally, with this information at hand, *AS-MAC* provides a flexible facility for the *ASN* nodes (*AN*s) to use those resources for their communication, while satisfying the above-mentioned constraints (*i*)-(*iii*).

The contribution of this paper is the identification of technical challenges in the development of a *PRI-SEC* system, and a practical solution proposed based on the *AS-MAC* protocol. Our evaluation of the protocol indicates that *AS-MAC* enables the *ASN* to efficiently utilize up to 80% of the otherwise unused bandwidth of the *GSM PRI* in a single-hop scenario. Moreover, when the *ASN* operates across a multihop topology, bandwidth reuse multiplies the benefit of the *ASN* deployment our performance evaluation section shows.

In the rest of the paper, we first provide an architectural view of the proposed system, identify the technical challenges therein, and discuss the basic ideas of our approach to address those challenges. The *AS-MAC* protocol is defined next, followed by its performance evaluation. Finally, we discuss related schemes in the literature and conclude with a discussion of future work.

*This work was supported by *DARPA/Raytheon Company* for the XG program under contract No. 12292

SYSTEM ARCHITECTURE AND OVERVIEW

An example of the physical architecture of the *PRI-SEC* system is illustrated in Figure 1: within the *GSM* system, *MS*'s communicate with the *BS*, while *AN*s form a multi-hop, peer-to-peer topology within the same *GSM* cell. Within a *GSM* cell, a set, *C*, of channel pairs, that is, frequency bands is allocated for use by the *BS* and *MS*'s, out of $C_{total}=124$ available *GSM* bands [14]. For each pair, one channel is used for *BS* to *MS* (*downlink*) and one channel for *MS* to *BS* (*uplink*) communication. Each up- or down-link is divided into T_S time slots. The *BS* transmits on dedicated slots in the downlink channel, the Frequency Correction Channel (*FCCH*) and Synchronization Channel (*SCH*), signals to enable the *MS*'s to achieve time synchronization with the *BS*. These are signaling channels and are point-to-multipoint.

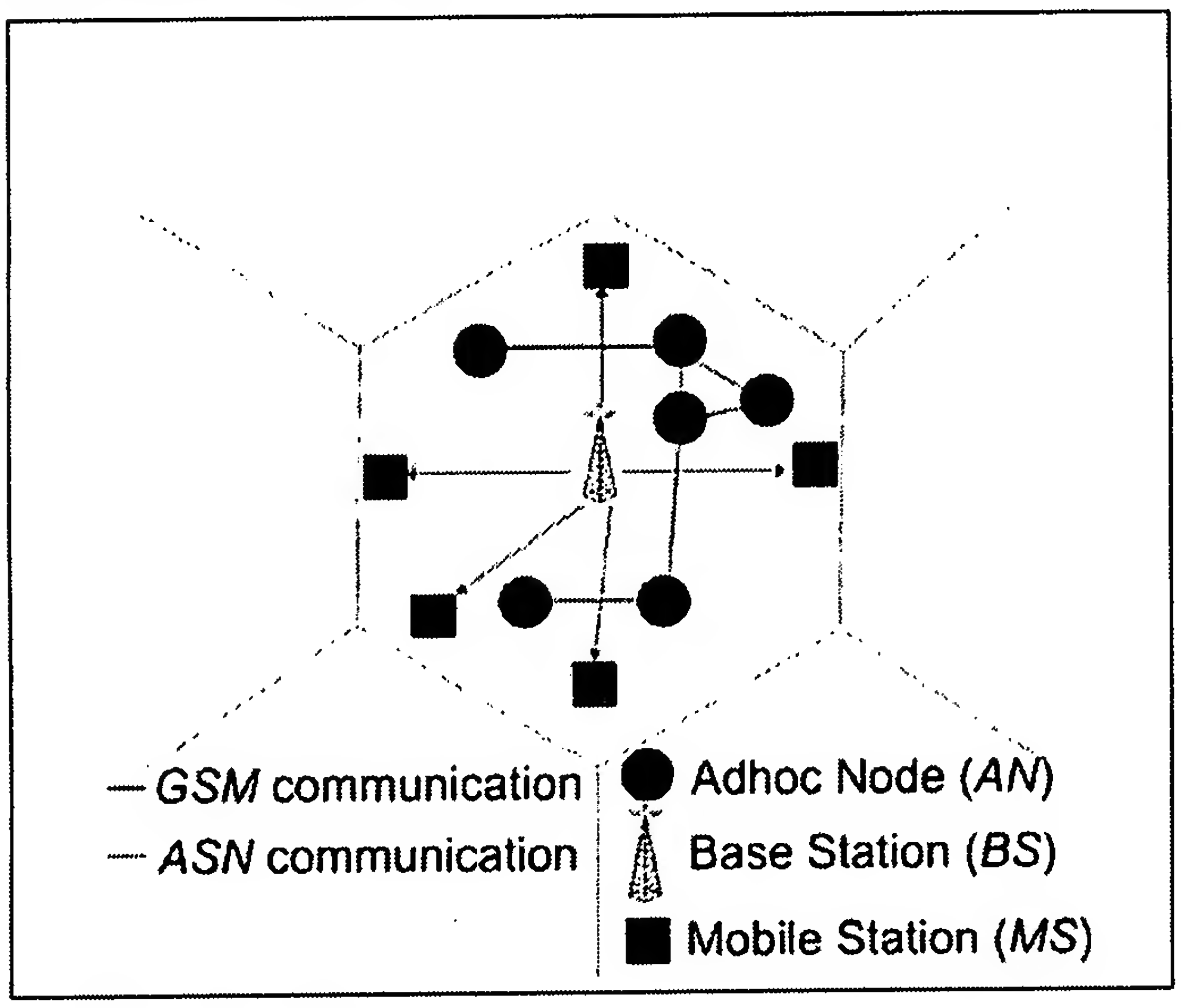

Figure 1. System diagram

Each of the *AN*s within an *ASN*, needs to first detect the communication structure of the *PRI*, and then identify the available resources, which are the time-slots within each of the cell's frequency bands. Then, the *AN*s utilize this available bandwidth to communicate, without interfering with the operation of the *PRI*. We note that the *ASN* can operate across multiple cells, yet we leave this as future work.

The first challenge for *ASN* is to detect the *PRI* communication structure and identify the available resources. To do so, we assume that *AN*s are equipped with a *sensing module*, that is, hardware that provides the capability for wide-band spectrum sensing [15], [19], [20]. For our system, it suffices that the sensing module detects the presence of a signal (that is, energy level above a threshold) within each of the *C* bands. The *AN*s equipped with the sensing module first detect the *C* bands in use in the cell. Then, they obtain the slots boundaries (i.e. the beginning and end of each time-slot) by decoding the *FCCH* and *SCH* signaling. Finally, the sensing module is used to construct an up-to-date map of available time slots. With a complete picture of the slot availability on the downlinks, *AN*s can communicate among themselves. More importantly, by transmitting during slots sensed and guaranteed to be idle, *AN*s ensure that there will be no collision with or obstruction of the *PRI* traffic.

Note that only the resources on the downlinks are utilized by the system described in this paper, as determining the boundaries of the slots in the uplinks would require the collaboration of the *PRI* (i.e., the *BS*). We assume that *AN*s use the *GSM* physical layer, below the *FDMA/TDMA GSM* medium access to communicate among themselves within the *ASN*.

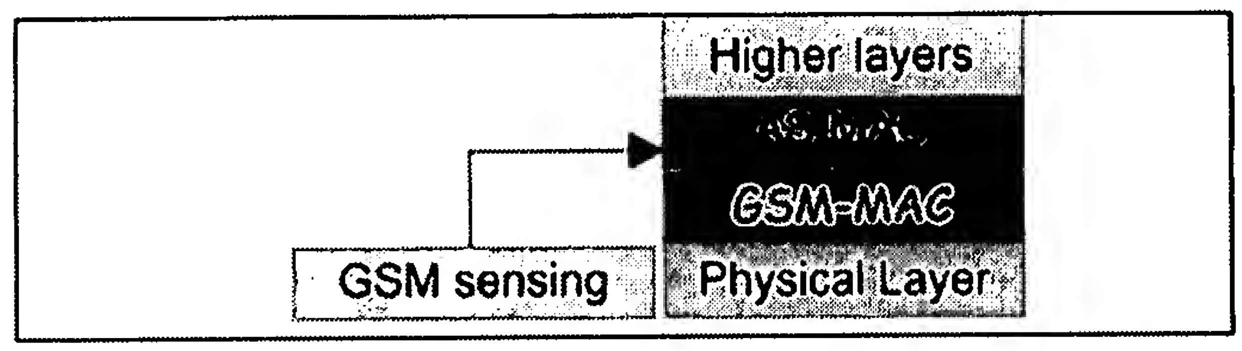

Figure 2. Protocol stack of *AN*

The solution we are after seeks to enable any network protocol stack in the *ASN*. Nonetheless, the challenge lies in transmitting a packet from the *ASN* network across the available spectrum, and dependent only on the *PRI* operation and traffic resources. To achieve this goal, a protocol that acts as an intermediary between the *ASN* network layer and the primary *GSM* system is necessary. Essentially, such a protocol acts as a medium access control protocol from the point of view of the *ASN*. Yet, it is not truly a medium access control (*MAC*) protocol, as it operates on top of the *GSM MAC* protocol. We denote this protocol as *Ad hoc Secondary Medium Access Control* (*AS-MAC*). Figure 2 illustrates the *ASN* protocol stack.

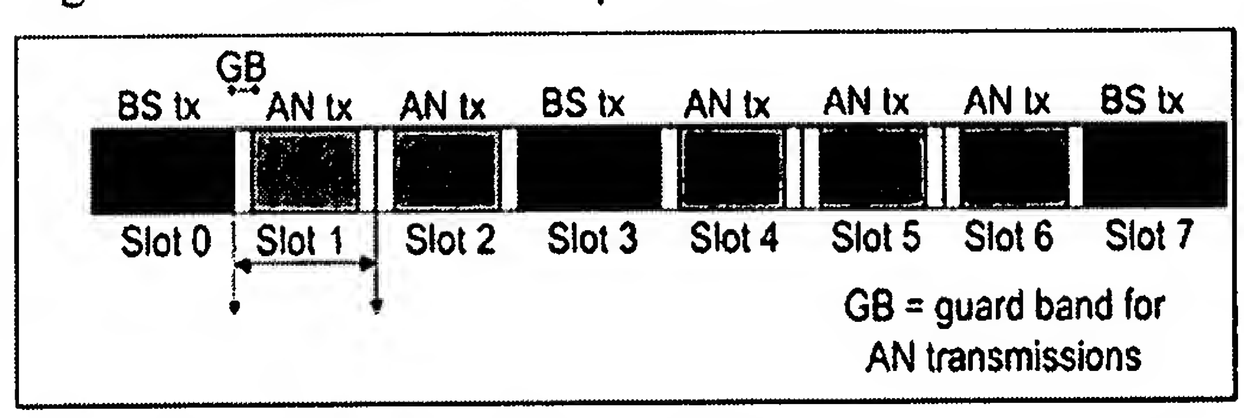

Figure 3. GSM Slot Utilization by ASN nodes

The *AN*s have only one transceiver, while multiple *GSM* channels are available. As a result, the *AS-MAC* provides for the selection of one among those channels. To do so, a handshake is necessary between the sender and the receiver: the sender provides candidate channels and the receiver selects a desirable channel. Then, not only the two

nodes but also their neighbors can be aware of the channel in use. This exchange of information is performed across a commonly agreed channel, which we denote as the *control channel* (*CC*), while the actual data transmission takes place across the remaining data channels.

Finally, once the data channel is selected, *AS-MAC* has to actually transmit the data. The challenge here is that the transmission has to take place within the available slots. Essentially, to ensure non-interference with the *PRI*, *AN*s 'hijack' free *GSM* slots, once it is definite that the slot is not utilized. Figure 3 shows a single time-slotted *GSM* downlink consisting of eight slots numbered *0* to *7*, with slots *0*, *3*, and *7* used by the *PRI*. Since the occupancy (availability) of slots depends on the *PRI* traffic, time progress of the *ASN* protocol, in our case *AS-MAC*, must take place only when *PRI* slots are free. Otherwise, the state of the *ASN* protocol must essentially freeze. For example, in Figure 3, if a message transmission is to occupy three slots, starting from Slot 1, then, counting those slots must 'stop' during Slot 3. In general, the *ASN* packets are larger than the number of bits that can be transmitted in a single *GSM* slot. Thus, the sender needs to fragment data and send it over successive free slots which may not be consecutive.

AS-MAC PROTOCOL OPERATION

First, we discuss how *ANs* make use of their sensing hardware, to identify and use *PRI* channel and unused slots. Then, we present the operation of our *AS-MAC* protocol, and finally discuss additional implementation aspects of the protocol.

A. SENSING AND CHANNEL USAGE

ANs identify the *GSM* downlinks in a *PRI* cell basically through sensing and the following steps. First, the *AN*s scan the *PRI* bands to determine the *FCCH* and *SCH* signaling channels, detecting the specific transmission pattern of those channels [14]. This way, *AN*s obtain the timing information of the slot boundaries. With this information in hand, *AN*s scan again the set of *PRI* channels specified to be used as downlinks, searching for those in use within the cell. To determine if indeed a downlink is in use, *AN*s sense within the boundaries only. If the sensed signals fit the slots, *AN* infers that this signal is transmitted by *BS*.

Note that it is possible that a node receives signals from multiple base stations, for example, when it is close to the boundary of two cells. By measuring the received signal strength, similarly to the *RSSI* measurements [14] performed by the mobile nodes, the node can classify the signals. Yet, it is possible that the in-use channel information is not the same across all *ANs*. This can be somewhat detrimental to the performance of the *ASN*, but as it will become clearer below, the network can operate as pairs of sender-receiver *AN*s communicate always on a mutually agreed data channel.

Among the available channels, *AN*s follow a convention to choose the downlink *GSM* control channel, exclusively for *AS-MAC* control traffic. In our design, the downlink that bears the *FCCH* and *SCH* signaling is the one utilized as the *AS-MAC* control channel. This is the first downlink channel identified by *AN*s and any new *AN* joining the *ASN* within the cell can unambiguously identify it. The set of remaining channels, denoted as C_d, are used for data traffic.

At all times, *ANs* determine whether a given slot is free. To ensure that a slot is indeed left unused by the *PRI*, *AN*'s sense the all (downlink) channels during a period of time τ at the beginning of each slot. It suffices that τ is of the order of $5\mu s$, after the *GSM* guard band ($15\mu s$). Overall, the required sensing time (after the guard band) is a small fraction of T the *GSM* slot duration of $577\mu s$. Through the sensing operation, *ANs* build and dynamically update a data structure, *pUsage* which maintains statistics of the *PRI* slot usage history, with more recent sample having higher weights. This information is used in dynamically selecting the preferred data channels for packet transmission. Nonetheless, such preference does not guarantee that the slot availability will remain as estimated, or does imply that any prediction of future usage is made. Instead, the sensing module is utilized at all slot boundaries to actually determine the slot availability.

It is straightforward to utilize the sensing module, which is utilized only for τ to sense *PRI* traffic, for sensing of *ASN* transmission. It suffices to activate the sensing module for a τ_{SEC} after the primary signal sensing. We denote this a *secondary sensing*, performed both on the *ASN's* control and data channels. Due to secondary and the control traffic, as explained below, *AN*'s maintain s*Usage*, a data structure indicating the data channels is currently in use by other *AN*'s.

B. *AS-MAC* DESCRIPTION

With the resource availability information at hand, *AS-MAC* enables communication between any two neighboring *AN*s. Basically, *AS-MAC* provides the means for nodes to first agree upon a data channel, through a handshake that involves the exchange of three control messages, a *Request To Send* (*RTS*), a *Clear To Send* (*CTS*), and a *Reservation* (*RES*) message transmitted in this order. Our experiments, presented in the performance evaluation section showed that the *RES* message may not be necessary. As a result, we identify and discuss two versions of *AS-MAC*, one which uses *RES* and we denote as *AS-MAC*$_1$, and one without *RES* denoted as *AS-MAC*$_2$. Since the latter is found more efficient, we discuss this variant below, referring to

$AS\text{-}MAC_1$ and $AS\text{-}MAC_2$ interchangeably unless otherwise noted.

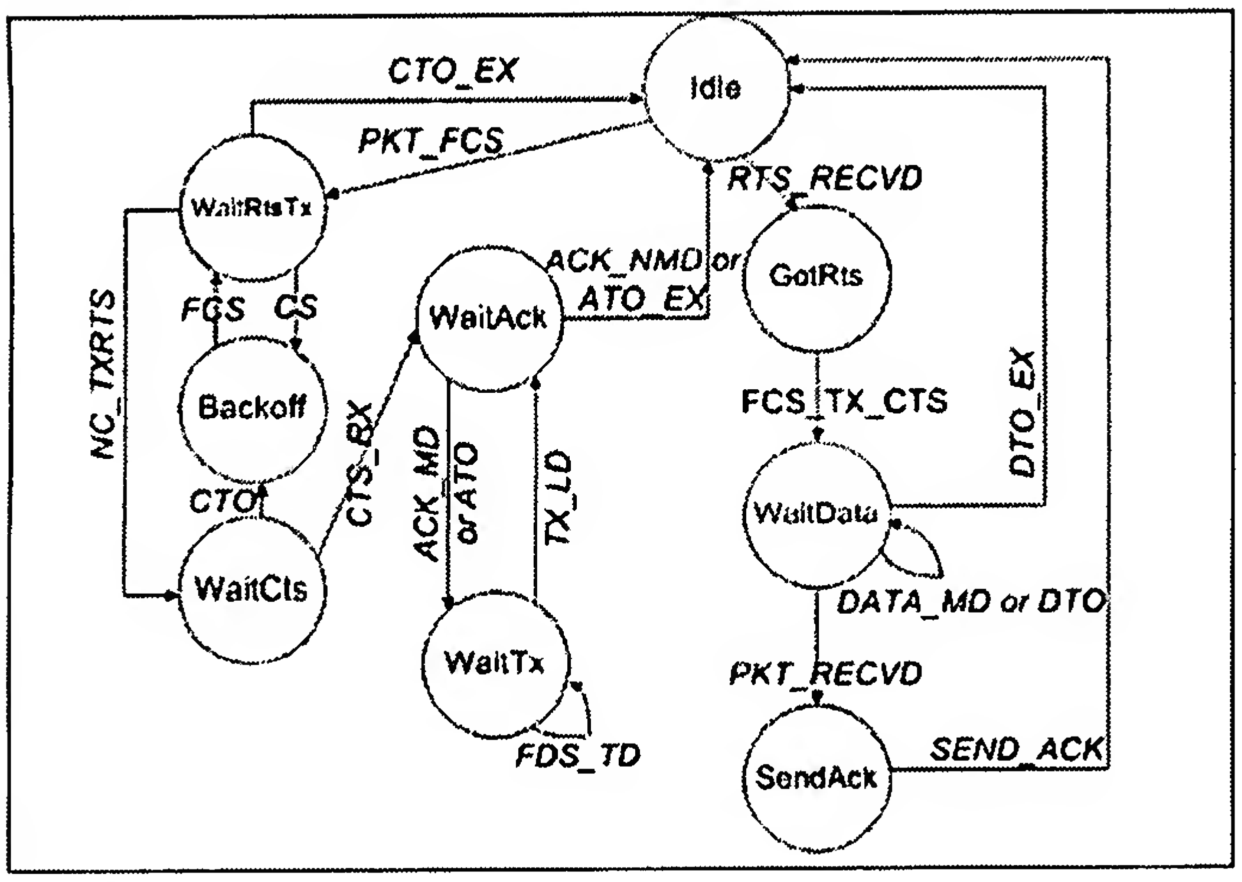

Figure 4: *AS-MAC* state transition diagram

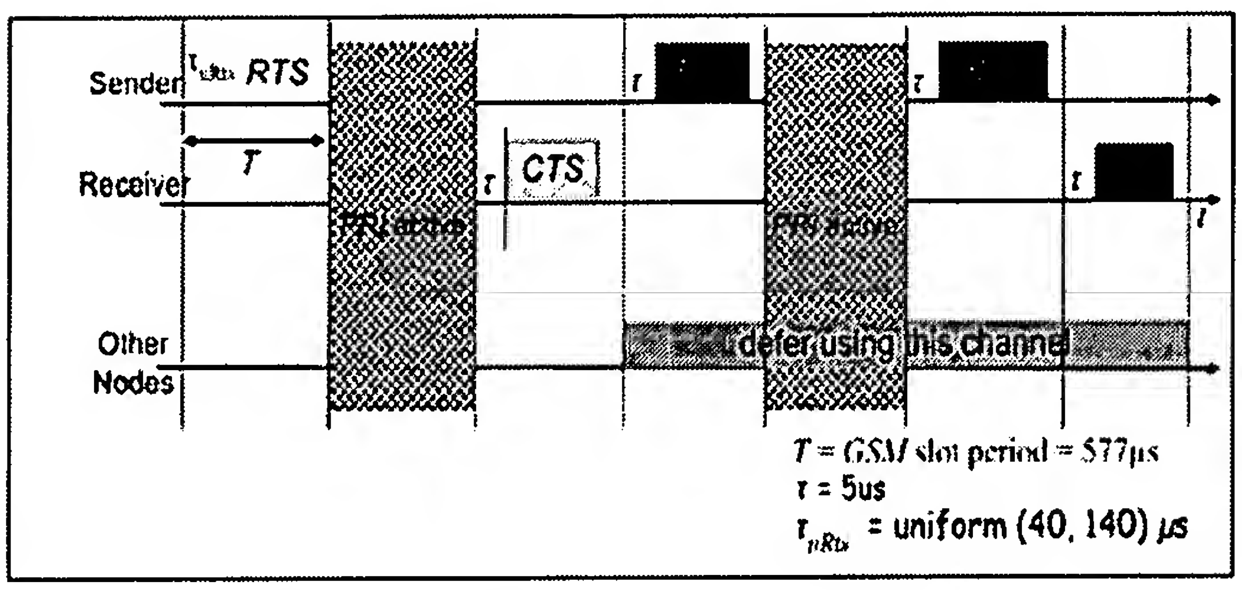

Figure 5. *AS-MAC* packet transfer

The finite state diagram in Figure 4 defines the *AS-MAC*, with Table 1 explaining the conditions and actions for each transition. Figure 5 illustrates the *AS-MAC* operation.

When an *AN* has an eligible packet to transmit, it waits for a free control slot. A packet is eligible for transmission if the destination is not currently involved in communication with some other node as indicated by *CTS* and *RES* received by the *AN*. It then schedules a unicast *RTS* transmission after τ_{uRts} which is uniform in a window W_{uRts}. This is done to introduce some randomness in *RTS* transmissions so that collisions among *RTS* are reduced. W_{uRts} is set to (40μs to 140) μs from slot beginning. When the scheduled waiting time for *RTS* transmission expires, *AN* senses the control channel. If it is found busy, *AN* retries the *RTS* in the next free control slot without incrementing the backoff counter.

If no carrier is sensed, *AN* sends *RTS* as shown in Figure 5. The *RTS* contains a bit map of channel status from the perspective of the sender, the number of slots needed to transmit the packet (called *NAV*). After sending *RTS*, the sender waits until the end of the next free slot on the selected data channel to receive *CTS*. This is an important point because, if the sender were to wait for just one slot duration and if the next slot were to be used by *GSM*, the receiver will not transmit *CTS*. Then the sender would timeout unnecessarily. Similar phenomenon happens for all timeouts in the protocol.

Condition/Action Id	Description
PKT_FCS	Packet available and free control slot / schedule *RTS* transmission
CTO	*Timeout / ++numCtsTimeouts*
CTS_RX	*CTS* received
CS	Carrier sensed
NC_TXRTS	No carrier / Tx *RTS*
FDS_TD	Free data slot and more than one *DATA*/ tx *DATA*
ACK_MD	*ACK* recvd and more *DATA*
ATO	*ACK* timeout / *++numAckTimeouts*
TX_LD	Free data slot and only one pending *DATA* / tx *DATA*
ACK_NMD	*ACK* got and no more pending *DATA*
FCS	Free control slot
SEND_ACK	Free data slot / send *ACK*
ATO_EX	*MAX_ACK_TIMEOUTS* exceeded / drop packet
FCS_TX_CTS	Free control slot / send *CTS*
RTS_RECVD	Unicast *RTS* recvd
PKT_RECVD	Packet received completely / pass packet to higher layer
CTO_EX	*MAX_CTS_TIMEOUTS* exceeded / drop packet
DTO_EX	*MAX_DATA_TIMEOUTS* exceeded / drop packet
DATA_MD	*DATA* fragment got, more *DATA* pending
DTO	*DATA* timeout / *numDataTimeouts++*

Table 1: *AS-MAC* protocol conditions and actions

If *CTS* is not received by the sender, backoff counter is incremented and *RTS* is retried in the next free control slot. Once *MAX_RTS_ATTEMPTS* are exceeded, the packet is dropped. On receipt of *RTS*, receiver sends *CTS* as shown in Figure 5 which contains the receiver's and sender's Id, *NAV*, and also the channel selected for communication. The receiver selects that data channel which is free both at the sender and at the receiver, and which has the maximum number of free slots available.

On receipt of *CTS*, sender sends *RES* in the case of *AS-MAC_I*. This is depicted in Figure 5. *RES* contains sender and receiver Ids, NAV info, and the channel chosen for data transfer. Other nodes that receive (*RES* and) *CTS*, know that they should prohibit themselves from using the specified channel until at least *NAV* number of free slots have passed by on the chosen data channel. *RES* and *CTS* also tell other *ANs* not to attempt to send an *RTS* to the sender or the receiver as they will be busy in a data transfer and therefore cannot receive *RTS*.

After the sender and receiver complete the *RTS/CTS* (*RES*) handshake, the sender fragments the packet and transmits the fragments successively on all the free slots on the data channel. Figure 5 and Figure 6 indicate this operation and also illustrate that *AS-MAC* does nothing in a slot that is being used by *PRI*. Fragments are identified by a sequence number beginning from zero. An *ACK* is expected by the sender when there are no more pending fragments to send. This is indicated to the receiver by setting the *ACK* flag in the header. A *FINAL* flag is also set whenever the sender sends the last fragment of the packet. *ACK* from the receiver contains a bitmap acknowledging the fragment *Ids* received in the current cycle (cycle refers to the time period in which one train of fragments is sent by the sender and an *ACK* is sent by the receiver).

Here it is interesting to note that the sender does not reserve a channel for any fixed duration of time as is the case with 802.11 and Multi-channel MAC (*MMAC)* protocols in general. This will not work because, the secondary cannot know the future channel/slot usage of the primary, so it has no way of telling when it will be done transmitting. Thus *AS-MAC* uses a count of the number of free slots that is required for transmitting the data packet as the *NAV*. Third party *ANs* that receive the *CTS* and *RES*, decrement the *NAV* counter only when a free slot passes by on the selected data channel.

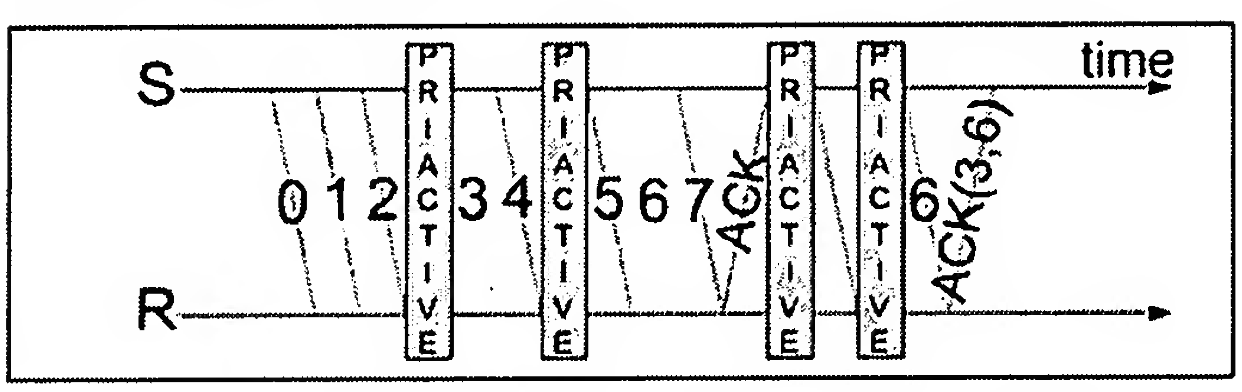

Figure 6. *AS-MAC* error recovery process

On receipt of *ACK*, the sender updates its knowledge of successfully received fragments and retransmits only the unsuccessful fragments. When the sender sends the last pending fragment it always expects an *ACK*. This process is continued until the entire packet is transferred. An example error recovery situation is illustrated in Figure 6 for the case of a packet consisting of eight fragments numbered 0 to 8. Fragments 3 and 6 are lost (shown in dotted lines). The first *ACK* acknowledges all fragments except 3 and 6 which are then retransmitted in the next cycle and the packet transfer is completed.

On receipt of a packet with the *FINAL* flag set, the receiver knows that the last fragment has been received. Thereafter, on receipt of every fragment, the receiver checks to see if it has then received all the fragments. If so, the entire packet has been received and is passed on to the higher layer.

One problem arises when a large packet needs to be transmitted. *ACK* packet needs to fit into one slot, so there is an upper bound on the number of bits available for acknowledging received fragments which means that the receiver cannot acknowledge an arbitrarily large number of fragments. In this case, the sender restricts the number of fragments to be sent in a cycle to a suitable value. The remaining fragments and any fragment not received successfully in the current cycle are transmitted in the next cycle.

C. *AS-MAC* IMPLEMENTATION CONSIDERATIONS

Next, we discuss issues related to the ASN transceivers. First, consider the transceiver turnaround time, that is, the period of time needed for a transceiver to switch from transmitting to receiving mode and vice-versa. In our system, such transitions need to occur at the *PRI* slot boundaries. The aggregate time of the *GSM* guard band (*15μs*), the *PRI* sensing period (*5μs*), and the margin of *27μs* to ensure negligible interference on *PRI* transmissions, is well above the 802.11g receive-to-transmit and transmit-to-receive turnaround times of *5μs* and *10μs* for its *DHSS*.

Another concern is the time needed to dynamically switch a transceiver to different channels at different points in time. In *AS_MAC* such switching needs to take place after a *RTS-CTS* handshake and after the transmission of a packet when the sender and receiver want to switch to the control channel. The channel switching time allowed in *802.11* is *224μs*. Thus it seems impractical in the near future to achieve switching times less than about *45μs*. To overcome this problem we suggest that both the sender and receiver freeze their operation in the next slot (irrespective of whether it is free or not) after the RTS-*CTS* handshake and resume the protocol operation thereafter. This allows ample time (at least full slot duration of 577μs) to switch the transceiver to the chosen data channel.

It is important that time synchronization of *ASN* with *BS* be maintained all throughout. This necessitates *ANs* to update their time reference by listening to the *FCCH* and *SCH* messages from *BS* periodically. *ANs* could do this a few times a second whenever they are not transmitting a packet. It may be noted that *MSs* get such timing information from BS twice per second (when a call is in progress).

PERFORMANCE EVALUATION

We evaluate the performance of our system, studying the improvement in spectrum utilization due to the *ASN*. We denote the % of bandwidth utilized by the *PRI* when deployed alone as PRI_U, and % of bandwidth utilized by the *PRI* and the *ASN* when both are deployed as PRI_ASN_U. We quantify this improvement with two metrics: (i) the spectrum utilization improvement, $SUI=(PRI\_ASN_U - PRI_U) / PRI_U$, and (ii) the utilization of available bandwidth *BU*, calculated as the fraction of the bandwidth used by *ANs* over the *PRI* left-unused downlink bandwidth. Both *SUI* and *BU* are calculated as averages over the total duration of the simulation. *BU* quantifies the effectiveness of our *AS-MAC* and *SUI* provides the overall picture of efficient utilization. Our results indicate that *AS-MAC* is effective, with *BU* up to *83%*, thus yielding up to *SUI* of *40%* in a single-hop setting and even more in multi-hop setting due to spatial reuse.

We use Qualnet [17] for the simulations of a single-hop as well as a *10*-by-*10* grid topology of *100 ANs*, with transmission and carrier sensing range set to *250m* and *625m* respectively. The capture threshold and the required *SINR* for successful reception are set to *10dB*; ambient noise is assumed to be negligible, but errors are caused by interference. All *AN*s are within one cell of the *PRI GSM* system, with $C = 8$ channel pairs, in use within the cell. One of the channels (the one with the lowest index) is assumed to be the control channel for *AN*s, and the remaining *7* channels are denoted as data channels. The *PRI* traffic occupies one or more time slots within each channel. We assume that the slot occupancy (availability) changes slowly compared to a packet transmission, as call holding times are in the order of few tens of seconds to minutes [14]. We vary the % of available slots in the control and data channels, with values from *25%* (*2* out of *8* slots per *GSM* frame) to *100%* (*8* out of *8* slots), denoting the % of available slots in each control and data channel as B_C and B_D. The *ANs* operate in saturation conditions, always having a packet to send. *ANs* randomly select a neighbor to transmit a packet, with size fixed at *280* bytes including the *UDP* and *IP* headers. We show the performance of the two versions of *AS-MAC* we discussed above, *AS-MAC*$_1$ and *AS-MAC*$_2$.

The main objective of *AS-MAC* is to improve spectrum utilization. Recall however that, in the system evaluated here, the *ASN* utilizes only the downlinks. Thus, at most only half of the total amount of *GSM* bandwidth left unused can be utilized (assuming symmetric *GSM* traffic as in the case of voice calls). Table 2 shows the performance of *AS-MAC*$_2$ in a single-hop environment with 40 co-located nodes, as a function of B_C while B_D=*50%*. *ASN* improve the bandwidth utilization up to *41.6%* when control bandwidth availability is B_C=*100%*, amounting to *BU*=*83.2%* and *SUI* up to *41.6%*. As B_C decreases, the control channel gradually becomes a bottleneck, yet *BU* degrades gracefully to *70%* for B_C=*25%* and *SUI* remains equal to *35%*.

% B_C	25	37.5	50	62.5	75	87.5	100
%BU	70.0	80.2	82.8	82.6	83.2	82.8	83.2
%SUI	35.0	40.1	41.4	41.3	41.6	41.4	41.6

Table 2: Spectrum utilized by *ASN* (AS_MAC$_2$) in a single hop network, as a function of %*ACB* (available control bandwidth)

In a multi-hop *ASN*, *AS-MAC* can perform even better due to spatial reuse of the available bandwidth. Thus in this case *SUI* and *BU* can be more than (*100%* - PRI_u). We now consider the multi-hop grid topology. Figure 7 shows *BU* when B_D = *25%* and *50%*, as a function of B_c. We do not take the control channel bandwidth into account in these calculations. In that case, the spectrum utilized by *ASN* would be slightly less than what our graphs indicate, yet the trends will remain the same.

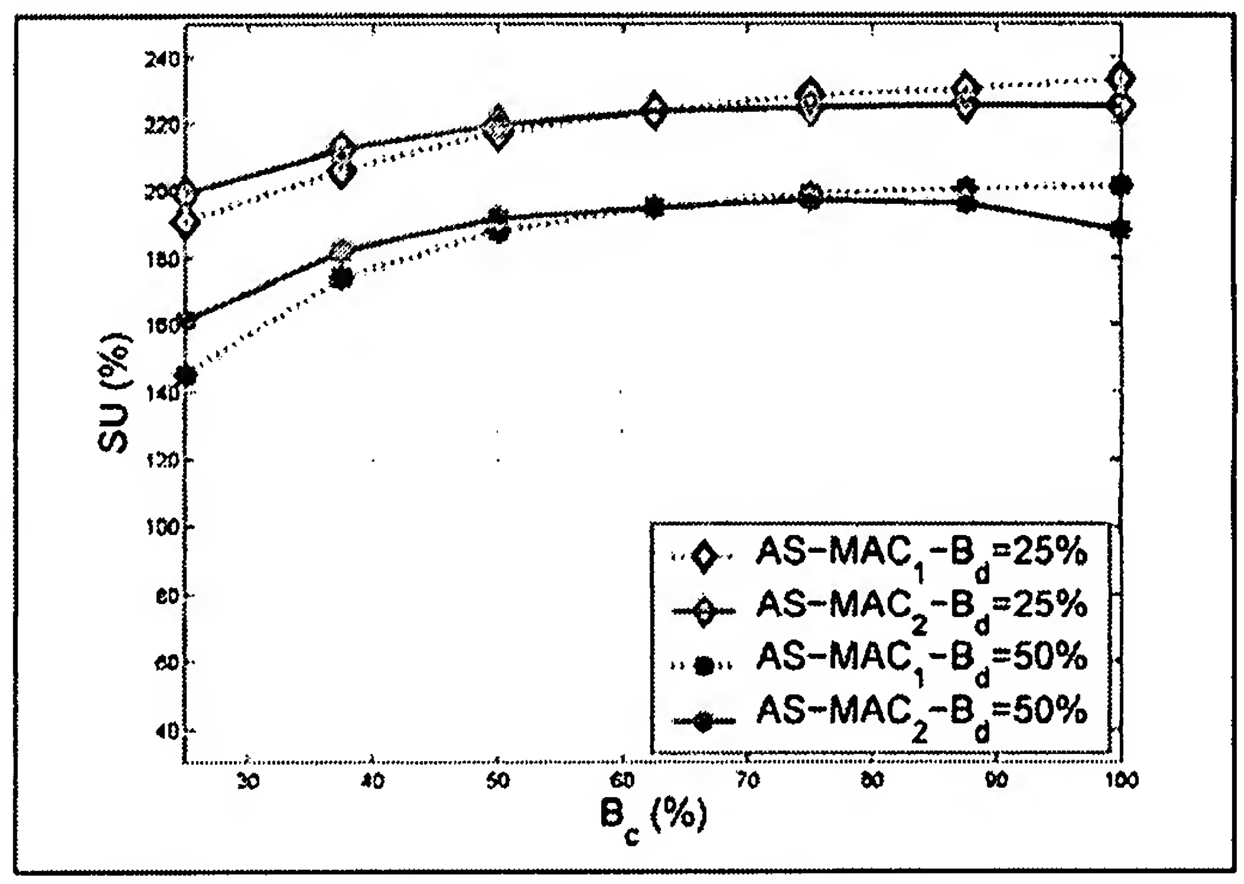

Figure 7. % *BU* when B_d= 25% and 50%, Vs B_c

We observe that for lower values of B_c (i.e. when control bandwidth is the bottleneck) *AS_MAC*$_2$ performs the best as it needs less control bandwidth since it does not use *RES*. But as B_c is increased beyond about *60%*, *AS_MAC*$_1$ starts performing better than *AS_MAC*$_2$ as the control bandwidth is no more a bottleneck and the additional *RES* that *AS_MAC*$_1$ uses brings in some benefits. But even when the available control bandwidth is *100%*, *AS_MAC*$_1$ performs only marginally better than *AS_MAC*$_2$. In Figure 7, the comparison between *AS_MAC*$_1$ and *AS_MAC*$_2$ goes as *233.2%* to *225%* when B_d = *25%* and *201%* to *188%* when B_d = *50%*. This means that the use of the additional *RES* control packet is not very useful. Note that *AS-MAC*$_2$ achieves *BU* of about *188%* when B_c = *100%*. Comparing this with the utilization in the single-hop case of *83%* (as

illustrated in Table 2 and the related discussion), we see that the gain due to spatial reuse in this case is about *2.5*. Thus our protocol can perform significantly better in the multi-hop case than in the single-hop case.

When only one transceiver is available, the protocols suffer from the multi-channel hidden terminal problem (*MHTP*) [6]. This means that the nodes will not be able to receive a significant number of control packets. This makes one think that the lack of utilization improvement when using *RES* is due to the nodes not being able to receive it rather than the additional *RES* not being effective. Thus we show the results when two transceivers are used by *ANs* in Figure 8 when $B_d = 25\%$ and $B_d = 50\%$. Now there is no hidden terminal problem as one of the transceivers always listens to the control channel. Still we see that the performance achieved by AS_MAC_1 compared to AS_MAC_2 is still marginal (*235%* to *230%* when $B_d = 25\%$, and *211%* to *203%* when $B_d = 50\%$). Thus, it is evident that the use of an additional *RES* packet in the control handshake is not very useful when multi-channel sensing is available and therefore can be safely avoided.

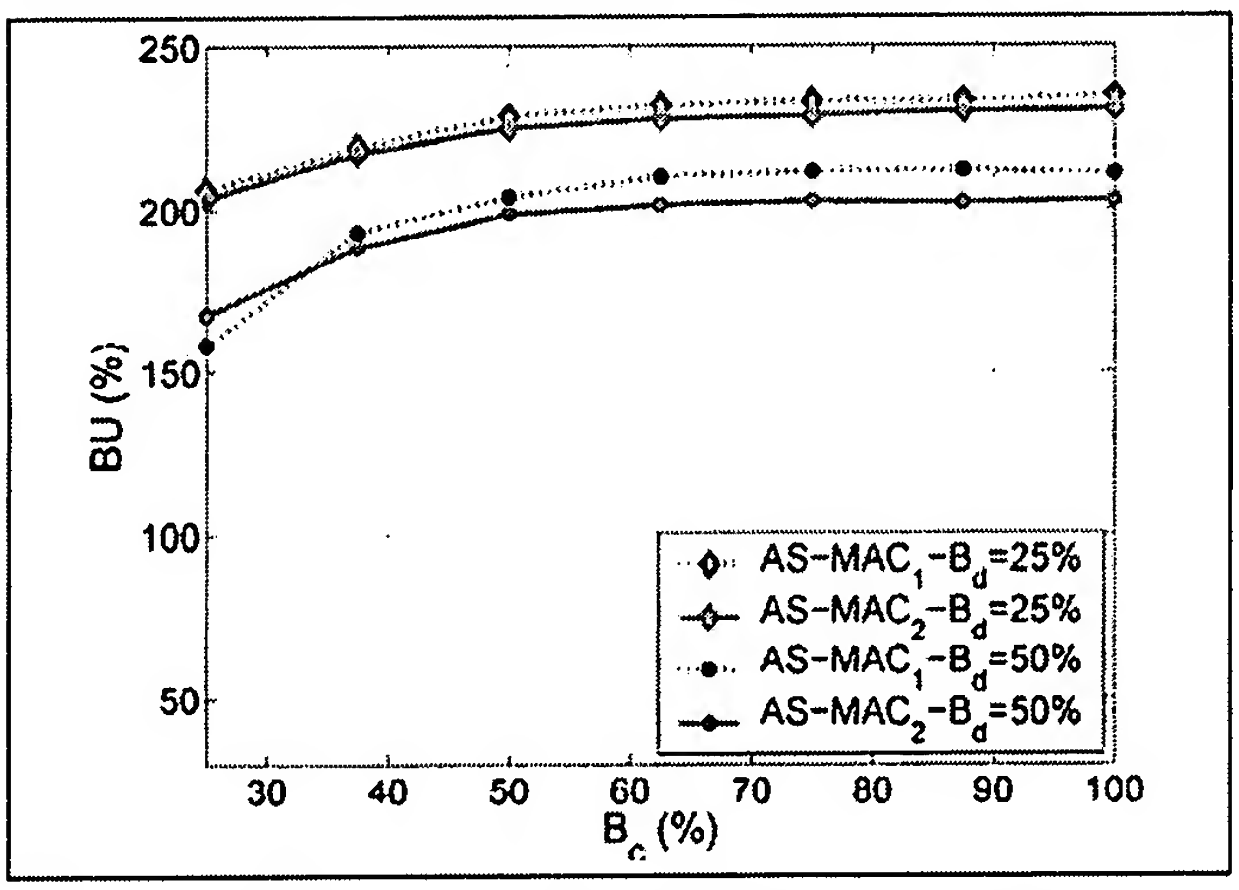

Figure 8. % *BU* when two transceivers are used and B_d= 25% and 50%, Vs B_c

A natural question that now arises is how useful is *RES* when multi-channel sensing is absent. The result of this scenario is shown in Figure 9. "NS" in the legend refers to no sensing being used. "1Tx" means *ANs* are equipped with only one transceiver and "2Tx" means they have two transceivers with one of them permanently listening to the control channel. It is seen that when sensing is absent, AS_MAC_1 performs better than AS_MAC_2 (*52.8%* to *33.6%* for 1Tx and *131%* to *53%*). The difference is much more pronounced for the "2Tx" as now the control packets are being received effectively. In the absence of sensing, *ANs* are fully dependent on *CTS* and *RES* packets for knowing channel status. When control packets are ignored, nodes end up choosing already busy channels leading to excessive collisions. This confirms that *RES* is important when sensing is absent but not so otherwise.

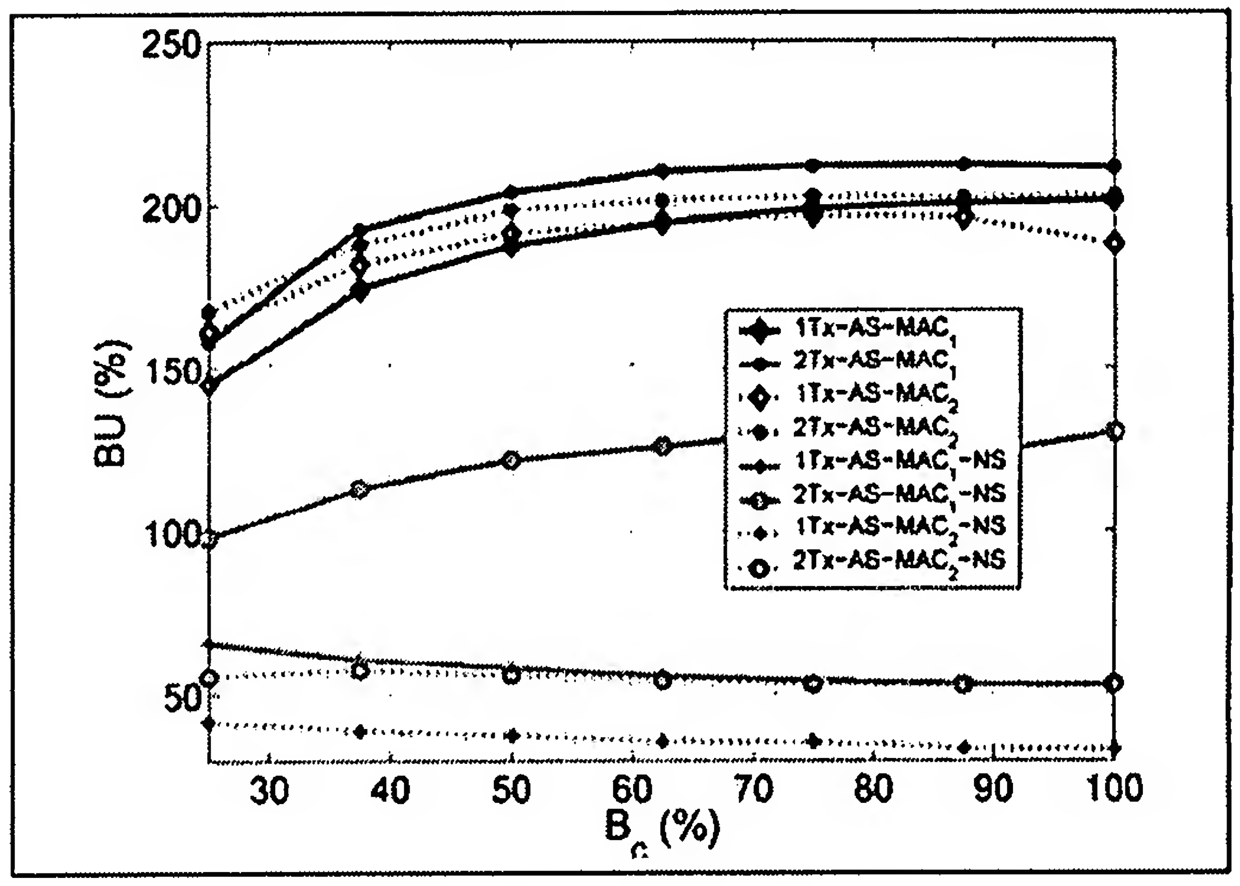

Figure 9. % *BU* Vs B_c when one or two transceivers are used in the presence and absence of sensing, and B_d = 50%

Figure 9 also shows how the presence of sensing helps mitigate *MHTP*. When *ANs* use only one transceiver ("1Tx") they suffer from *MHTP*. It is seen that the performance degradation due to *MHTP* when sensing is present is much less (*211%* to *201%* for AS_MAC_1, and *203%* to *188%* for AS_MAC_2), while as seen before the performance degradation is much more pronounced when sensing is absent. This illustrates that sensing makes the protocol robust to *MHTP*.

RELATED WORK

A small number of proposals in the literature have considered *PRI-SEC* systems. Two models of *PRI-SEC* interaction are introduced in [3]: the *PRI* is aware and attempts to accommodate the traffic of the *SEC*, or the *PRI* has full priority, and it is the responsibility of the *SEC* to avoid unacceptable levels of interference. The latter model is the one considered here. These two works propose spectrum pooling between a *GSM PRI* and an OFDM-based WLAN adopting the HIPERLAN standard [12] for the *SEC*. Our work is significantly different, as we develop an ad hoc *SEC* system that operates without fixed infrastructure. Moreover, we address a number of practical considerations regarding the interoperation with the *PRI GSM*, such as the SEC traffic transmission; for example, it is not clear how the *2ms* HIPERLAN frames correspond with the *GSM* slot width of about *0.5ms*. Moreover, our design has the advantage it is not strongly dependent on the physical layer.

Finally, [13] proposes two medium access control protocol designs for a single channel *PRI-SEC* configuration, assuming that the system has the capability to predict "spectrum holes" which are then used to transfer packets.

Beyond the different *PRI-SEC* configuration we consider, our work is not dependent on the prediction of resource availability and thus ensures non-interference between *PRI* and *SEC* to the extent that *ANs* are properly able to sense the spectrum. Moreover, ours is a multi-channel system.

Beyond the *PRI-SEC* context, a number of *Multi-Channel MAC* (*MMAC*) protocols were proposed. However, those are either inapplicable or inefficient and thus impractical in the *PRI-SEC* setting. [7], [8], [9] require that each node is equipped with a number of transceivers equal to number of channels, a clearly impractical assumption. [11] requires three transceivers, while a solution with two transceivers with one of them tuned constantly on the control channel to provide an up-to-date picture of the channels' state was proposed in [5] which uses an additional *RES* control packet. We have shown that *RES* is not beneficial in the presence of sensing, thereby reducing control overhead.

The asbsence of upto date channel status information is denoted as the Multi-Channel Hidden Terminal Problem (*MHTP*) [6] when the protocol operates with a single transceiver and thus alternates between data and control channel transmissions. A solution that alleviates this problem with the requirement that nodes are synchronized is presented in [6]. However, in a multihop setting, as is our *ASN*, the absence of synchronization (non-overlapping 802.11 ATIM windows) renders the scheme unusable. Finally, [10] proposes a single transceiver *MMAC* protocol, which addresses the *MHTP* at the expense of network performance. Nodes sense the targeted channels for a period of time equal to the maximum-size frame transmission; if an ACK is received (with *ACK*'s transmitted on the control channel rather than the data channel), or if the time-out expires the node knows that the channel(s) in question is released and contends for it. The long waiting periods thus introduced would be highly inefficient. This would not be justified in our setting as *AS-MAC* is already robust to *MHTP* due to the presence of sensing.

We also briefly note that *PRI-SEC* systems are fundamentally different from data-over-cellular services, such as *CDPD* [16] or *GPRS*. In these cases, the data transmission is actually undertaken by the *PRI* system while in our case *ASN* has to provide its service without any help from *PRI* and as such is much more challenging.

CONCLUSIONS

We outlined design principles for *AS-MAC* that enables efficient interworking of *GSM* and an ad-hoc overlay. Our *AS-MAC* is shown to improve the overall spectrum utilization by as much as *80%*. Our results also indicate that *RES* can be safely ignored in the presence of multi-channel sensing, thereby reducing the control overhead. Moreover, the presence of sensing helps overcome *MHTP*. The insights gained herein are expected to be applicable to general *MMAC* protocols as well. Thus, we expect channel sensing to play an important role in future systems. Given the large and growing base of deployed cellular infrastructure, it is highly likely that our contributions in the *PRI-SEC* setting we propose will be of immense practical use.

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A CDMA Overlay System Using Frequency-Diversity Spread Spectrum

Eckhard Papproth and Ghassan Kawas Kaleh

Abstract— **The frequency bands currently used by existing narrow-band users might be shared with a code-division multiple-access (CDMA) spread-spectrum (SS) overlay system. Thus, the spectral efficiency is improved, providing more capacity for future personal communications services. Since both narrow- and wide-band signals interfere with each other, an SS modulation scheme with a good resistance to narrow-band interference results in an increased number of acceptable overlay users. We study a frequency-diversity SS modulation scheme for which optimal detection in the presence of narrow-band interference is easy to implement. The acceptable number of overlay users is evaluated and compared to that of conventional direct-sequence SS (DS-SS) modulation schemes with and without interference rejection filters. The proposed system also presents the following advantage: by suppressing transmission of replicas where narrow-band signals (NBS's) are present, the mutual interference can be avoided completely.**

Index Terms— **Broad-band overlay, code-division multiple access, interference suppression, spread-spectrum communications.**

I. Introduction

Spread-spectrum (SS) techniques become more and more attractive for commercial applications like wireless LAN's and personal communications networks. With the expected wireless revolution in telecommunications, the available spectrum should be used efficiently and flexibly. One step in this direction is the use of SS overlay. Spectrum spreading allows overlaying signals on frequency bands which are already occupied by narrow-band users without influencing these in a considerable way [1]–[4]. Thus, the spectral efficiency of the spectrum usage is increased especially if the spectrum is only partly occupied by narrow-band signals (NBS's) or if these are active only every now and then. This is the case for most conventional users of the radio spectrum (like microwave links) and all kind of radio networks including narrow-band cellular radio systems. Usually, the regulatory body limits the maximum allowed interference from an overlay system that affects the NBS. Another field of application is an overlay transmission over the community access television (CATV) [5] and power-line networks where narrow-band and impulsive ingress interference affects the signaling.

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The direct-sequence SS (DS-SS) signal is proposed as an overlay in [1]–[4]. The conventional correlator (or matched filter) receiver of the DS-SS system, which is optimum in the presence of additive white Gaussian noise (AWGN), is suboptimum in the presence of nonwhite Gaussian interference. The optimum receiver is very complicated since it includes a cascade of an interference whitening filter, a matched filter, and then an optimum detector, e.g., the Viterbi sequence detector, which takes into account the presence of intersymbol interference introduced by the whitening filter. However, since a DS-SS signal is robust to the effect of intersymbol interference, the optimum detector can be replaced by a simple threshold symbol-by-symbol detector with negligible degradation. Also, the whitening filter is equivalent to the best [6], [7] interference rejector. Therefore, in order to improve the performance of the DS-SS system in the presence of narrow-band interferers, interference-rejection techniques should be used at the receiver as described in [8]. More complicated solutions based on state-space representation are derived in [9]–[12].

In this paper, we examine the use of a modulation scheme called frequency-diversity SS (FD-SS) [13] as an overlay. Comparisons of FD-SS with DS-SS and frequency-hopping SS (FH-SS) highlighting its benefits are given in [13] and [14], respectively. Since the FD-SS system is more resistant to the partial-band interference than conventional schemes, its radiated power is lower than conventional schemes, thus, the narrow-band emissions are less affected. Moreover, with less radiated power, the number of overlay SS users is increased—see the capacity expression in [15, (1.5)].

The uncoded FD-SS system consists in sending simultaneously L replicas of every data symbol over L subchannels with disjoint frequency supports. Such a technique is commonly called frequency diversity [16, p. 719]. To obtain code-division multiple access (CDMA), symbol replicas of a user are multiplied by chip symbols that constitute its signature. The requirement that subchannels be of disjoint frequency supports allows us to limit the interference effect to only a subset of the replicas. If the interference level is much larger than that of the background noise, the receiver can easily distinguish corrupted replicas from safe ones. Moreover, if side information on interference and noise levels is available (this is easily estimated and without the use of known reference symbols), optimum soft decision is possible. Otherwise, corrupted replicas are erased and the other replicas contribute alone to detection. This approach cannot be used in a DS-SS system because chip symbols are sent serially in time; all chips are equally affected by the narrow-band interference.

We consider in this paper a distortionless AWGN channel and show that in an overlay system, FD-SS gives the best error performance and the largest number of users when compared with DS-SS schemes. With the latter we examine conventional correlator receivers without and with interference rejection filters. Two kind of rejection filters will be considered: the linear prediction filter [6] and the linear interpolation filter [7]. These filters have ultimate theoretical performance bounds, and they are not as easy to implement as the FD-SS receiver. Moreover, they may be adaptive and, in this case, significant time and energy (when known reference symbols are transmitted) are needed to adjust their coefficients.

Also, the FD-SS scheme has the advantage that it can omit the transmission of a replica if there is a strong narrow-band interference in its corresponding frequency slot. Consequently, the narrow-band transmission is not perturbed at all and the wide-band SS users are not affected by narrow-band links. This will reduce the radiated SS energy and hence increase the number of SS users. With DS-SS, this possibility requires the use of a notch filter [3] which introduces signal distortion.

In Section II, we briefly review the FD-SS modulation scheme. Section III presents a simple coexistence model of narrow-band and wide-band users. In Section IV, we show the interference resistance advantage obtained with the FD-SS waveform. This result is exploited in Section V to examine its effect on system capacity for two scenarios of narrow-band links. In Section VI, we briefly consider the transmission over multipath channels. Conclusions are summarized in Section VII.

II. Frequency-Diversity Spread Spectrum

An FD-SS signal has the following base-band model [13]:

$$\begin{aligned} s(t) &= \sqrt{2E_s}\sum_{i\in\mathcal{I}}\sum_{l\in\mathcal{L}} a_i c_{il}\psi_l(t-iT) \\ \psi_l(t) &= g(t)e^{j2\pi lFt} \end{aligned} \tag{1}$$

with E_s is the symbol energy, $\mathcal{I}$ the time index set, $\mathcal{L} = \{0, 1, \ldots, L-1\}$ the set of replicas, $\{a_i;\ i \in \mathcal{I}\}$ a sequence of complex data symbols, T the symbol period, and F the subchannel bandwidth. F should be smaller than or equal to the bandwidth of a narrow-band user in order to be able to efficiently resolve the narrow-band interference pattern. The chip symbols $\{c_{il}\}$ are assumed to be uncorrelated for all i and l. They are complex with $|c_{il}|^2 = 1$. $g(t)$ is a square-root Nyquist pulse with rolloff factor α. For simplicity's sake, we choose $\alpha = 0$. Therefore, its Fourier transform $G(f)$ is a brick wall: $G(f) = \sqrt{T/L}$ for $|f| < 1/2T$, and zero otherwise. The same chip pulse shape is chosen also in practical DS-CDMA systems in order to minimize the variance of the multiple access interference [15]. This choice implies that $F = 1/T$. Therefore, $g(t)$ satisfies the following orthogonality condition:

$$\int_{-\infty}^{\infty} g(t-iT)g(t-jT)\,dt = \delta_{i,j}/L \tag{2}$$

where $\delta_{i,j} = 1$ if $i = j$ and zero otherwise. $L = |\mathcal{L}|$ is the number of distinct frequency replicas of the FD-SS signal which we call analogously spreading factor. The above description implies the following orthogonality relation:

$$\int_{-\infty}^{\infty} \psi_m(t-iT)\psi_n^*(t-jT) = \delta_{i,j}\delta_{m,n}/L. \tag{3}$$

Thus, the set $\{\psi_n(t-iT); n \in \mathcal{L}, i \in \mathcal{I}\}$ is an orthogonal basis for the signal space. The FD-SS signal can be implemented using polyphase filterbanks as described in [13]. This FD-SS signal together with some NBS's are depicted in Fig. 1.

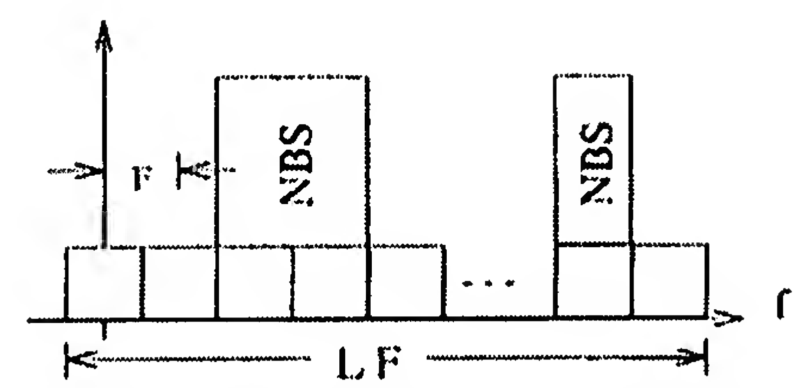

Fig. 1. The frequency-diversity SS waveform in presence of NBS's.

III. Coexistence Model

We define here a model for the coexistence of narrow-band and wide-band overlay signals in order to evaluate their mutual interference and the overall system capacity. To be able to compute error probabilities, all SS signals and NBS's are assumed Gaussian with flat power density in the assigned frequency band. Assuming a simple AWGN channel, the received base-band signal is the same for all SS and narrow-band receivers

$$r(t) = \sum_{m=1}^{M} s_m(t-\tau_m)e^{j\phi_m} + j(t) + n(t) \tag{4}$$

where the index m designates the mth user. It is the sum of the signals of M multiuser asynchronous wide-band SS signals, an interference term $j(t)$ representing the NBS's and the background noise $n(t)$. The time and phase offsets τ_m, ϕ_m are assumed as uniformly distributed and known at the respective receivers. Next, we give a characterization of the different signals, before we identify in the next section the signal to noise and interference ratios in the corresponding receivers. All wide-band SS signals transmit at the same symbol rate $1/T$ and are spread by a factor of L. We assume random uncorrelated signatures $\{c_{m,il}\}$ for all wide-band users, where the index m designates an SS user, i its symbol time, and l its chip time.

For the wide-band signals, we consider two types of spreading: DS and FD as described in Section II. The transmitted symbols $a_{m,i}$ are assumed to be complex with constant energy per symbol E_s and $|a_{m,i}|^2 = 1$.

Let $\mathcal{J}$ be a subset of $\mathcal{L}$ which contains the replicas of the FD-SS signals subject to the interference of NBS's. Thus, a fraction $\eta = |\mathcal{J}|/L$ of the available bandwidth is occupied by narrow-band emissions.

A. Background Noise

The background noise $n(t)$ is modeled as complex, Gaussian with zero mean and power spectral density $\Phi_n(f) = 2N_0$ over the SS signal band and zero otherwise.

B. Narrow-Band Signals

The sum of NBS's is denoted $j(t)$ in (4). It is assumed complex Gaussian with zero mean and power spectral density given by

$$\Phi_j(f) = \begin{cases} 2J_0, & kF - F/2 \le f < kF + F/2, \quad k \in \mathcal{J} \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

If the NBS in the kth band is a digital pulse-amplitude modulated signal, it would be expressed as

$$j_k(t) = \sqrt{2E_{s,N}L} \sum_{i \in \mathcal{I}} a_i \psi_k(t - iT)$$

where $E_{s,N}$ is the symbol energy and the other notations are as above. It is easy to show that the power spectral density of $j_k(t)$ is equal to $\Phi_j(f)$ if $J_0 = E_{s,N}$. Therefore, the performance measure J_0/N_0 that we use in Section IV is equivalent to the conventional performance measure $E_{s,N}/N_0$. This measure is also valid if the NBS carries analog information.

C. Frequency-Diversity Spread Signals (FD-SS)

The power spectral density of the mth wide-band user signal (1) is

$$\Phi_{m,W}(f) = \frac{2E_s}{T} \sum_{k=1}^{L} |G(f - kF)|^2 = \frac{2E_s}{L}. \tag{6}$$

It is constant over the whole SS signal bandwidth and zero otherwise, since the chip symbols are uncorrelated and $G(f) = \sqrt{T/L}$ for $|f| < 1/2T$ and zero otherwise.

D. Direct-Sequence Spread Signals

Let the chip pulse in a DS-SS system be a scaled version of the pulse $g(t)$ used for the replicas of the FD-SS signal. We have the following expression of the DS-SS signal associated with the mth user:

$$s_m(t) = \sqrt{2E_s L} \sum_{i \in \mathcal{I}} \sum_{l=1}^{L} a_{m,i} c_{m,il} g\left(tL - (iL + l)\frac{T}{L}\right). \tag{7}$$

Its power spectral density is constant over the whole signal bandwidth

$$\Phi_{m,W}(f) = \frac{2E_s}{L} \tag{8}$$

and the same as for the FD-SS signal.

IV. Performance Evaluation

Let $U_{m,i}$ be the decision variable for a symbol associated to user number m at time i. The error performance is a function of the mean and variance of $U_{m,i}$, conditioned on $a_{m,i}$. Therefore, we define a performance measure called the *signal-to-noise plus interference ratio*

$$\text{SNIR} = \frac{E^2[U_{m,i} \mid a_{m,i}]}{\text{Var}[U_{m,i} \mid a_{m,i}]}. \tag{9}$$

In fact, with uncoded QPSK or BPSK symbols and since the noise and interference are assumed Gaussian, the bit error probability is

$$P_e = Q(\sqrt{\text{SNIR}}) \tag{10}$$

with

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2}\, dt.$$

A. Receiver for NBS

As we have indicated in Section III, in the presence of background noise the performance measure for the narrow-band user is the ratio J_0/N_0. In the presence of interference from M SS users, the background noise with power density $2N_0$ is augmented by $M\Phi_{m,W}(f)$. Therefore, the performance measure becomes

$$\text{SNIR} = \frac{2J_0}{2N_0 + M\Phi_{m,W}(f)} = \frac{J_0}{N_0}\beta_N \tag{11}$$

$$\beta_N = \left(1 + \frac{M}{L}\frac{E_s}{N_0}\right)^{-1}. \tag{12}$$

B. Receiver for FD-SS Signal of User m

The FD-SS receiver performs L parallel matched filtering operations per symbol to obtain sufficient statistics $\{r_{m,il}\}$, $l \in \mathcal{L}$ and subsequentially combines them to yield a decision variable $U_{m,i}$ for symbol-by-symbol decisions on the ith symbol of user m

$$\begin{aligned} r_{m,il} &= \int r(t)\psi_l^*(t - iT - \tau_m)e^{-j\phi_m}\, dt \\ &= \frac{\sqrt{2E_s}}{L} a_{m,i}c_{m,il} + j_{m,il} + n_{m,il} \end{aligned} \tag{13}$$

where $r(t)$ is the received signal defined in (4). The contribution of narrow-band users is represented by $j_{m,il}$, that of background noise, and other SS users by $n_{m,il}$. Both contributions are independent, Gaussian of zero mean, and variance σ_j^2 and σ_n^2, respectively. We have

$$\sigma_n^2 = \frac{(M-1)}{L^2}2E_S + \frac{2N_0}{L}$$

$$\sigma_j^2 = \frac{2J_0}{L}.$$

As explained in [13], the samples are optimally combined to obtain the following symbol decision variable:

$$U_{m,i} = \sum_{l \in \mathcal{J}} \frac{r_{m,il}c_{m,il}^*}{\sigma_j^2 + \sigma_n^2} + \sum_{l \in \mathcal{S}} \frac{r_{m,il}c_{m,il}^*}{\sigma_n^2} \tag{14}$$

where $\mathcal{J}$ is the subset of $\mathcal{L}$ which contains the replicas of the FD-SS signal subject to the interference of NBS's. The subset $\mathcal{S}$ contains replicas without narrow-band interference. Thus, the reliability of the statistics $\{r_{m,il}\}$ is taken into account. It is easy to show that the performance measure is

$$\begin{aligned} \text{SNIR} &= \frac{E_s}{N_0}\beta_{\text{FD}} \\ \beta_{\text{FD}} &= \frac{\eta}{1 + \frac{M-1}{L}\frac{E_s}{N_0} + \frac{J_0}{N_0}} + \frac{1-\eta}{1 + \frac{M-1}{L}\frac{E_s}{N_0}} \end{aligned} \tag{15}$$

where $\eta = |\mathcal{J}|/L$.

C. Receiver for DS-SS Signal of User m

The conventional DS-SS receiver is composed of a receiver filter matched to the chip pulse followed by a sampler at the chip rate. After despreading and averaging one obtains the following decision variable:

$$U_{m,i} = \sqrt{2E_s}a_{m,i} + j_{m,i} + z_{m,i} + n_{m,i}$$

where $j_{m,i}$, $z_{m,i}$, $n_{m,i}$ are interference terms due to narrow-band, wide-band users and background noise, respectively. Their cumulated variance is

$$\sigma_{\rm DS}^2 = \frac{M-1}{L}2E_s + \eta 2J_0 + 2N_0.$$

The SNIR for the conventional receiver's decision variable is

$$\mathrm{SNIR}' = \frac{E_s}{N_0}\beta_{\rm DS}$$
$$\beta_{\rm DS} = \left(1 + \frac{M-1}{L}\frac{E_s}{N_0} + \eta\frac{J_0}{N_0}\right)^{-1}. \tag{16}$$

To enable a fair comparison with the FD-SS receiver, we have to consider an interference rejection filter in the DS-SS receiver, prior to despreading, to reduce the influence of the NBS's. To this end, we use the results of Masry [6], [7], which provide us with upper bounds for $\alpha_{\rm IRF}$, the SNIR improvement factor expressing the gain in SNIR obtained by the interference rejection filter (IRF). The upper bounds are the maximum SNIR improvement factors obtainable by using the best linear prediction and linear interpolation filter, respectively. As above, perfect side information about the power density of narrow-band emissions is assumed.

The improvement factors over the SNIR in (16) are for the prediction filter

$$\alpha_{\rm IRF} = \frac{a+b}{(1+b)^{1-\eta}\left(1+b+\frac{a}{\eta}\right)^{\eta} - 1} \tag{17}$$

and for the interpolation filter

$$\alpha_{\rm IRF} = \frac{a+b}{\frac{(1+b)[\eta(1+b)+a]}{\eta(1+b)+(1-\eta)a} - 1} \tag{18}$$

where

$$a = \frac{J_0}{E_s}\eta L \quad b = L\frac{N_0}{E_s} + M - 1.$$

Thus, with an interference rejection filter the SNIR of the DS-SS receiver is

$$\mathrm{SNIR} = \frac{E_s}{N_0}\beta_{\rm DS}\alpha_{\rm IRF}. \tag{19}$$

This figure reflects the performance of a receiver taking symbol-by-symbol decisions. The receiver that uses a linear interpolation filter is nearly optimal because the SS signal is robust to the effect of intersymbol interference (ISI). As the bandwidth expansion factor L approaches infinity, its error performance approaches that of the optimum receiver for a single ($M = 1$) wide-band user with narrow-band interference

$$\lim_{L\to\infty}\beta_{\rm DS}\alpha_{\rm IRF} = \lim_{L\to\infty}\beta_{\rm FD} = \beta_{\rm FD}|_{M=1}.$$

This is because the ISI tends to zero when the signal bandwidth tends to infinity.

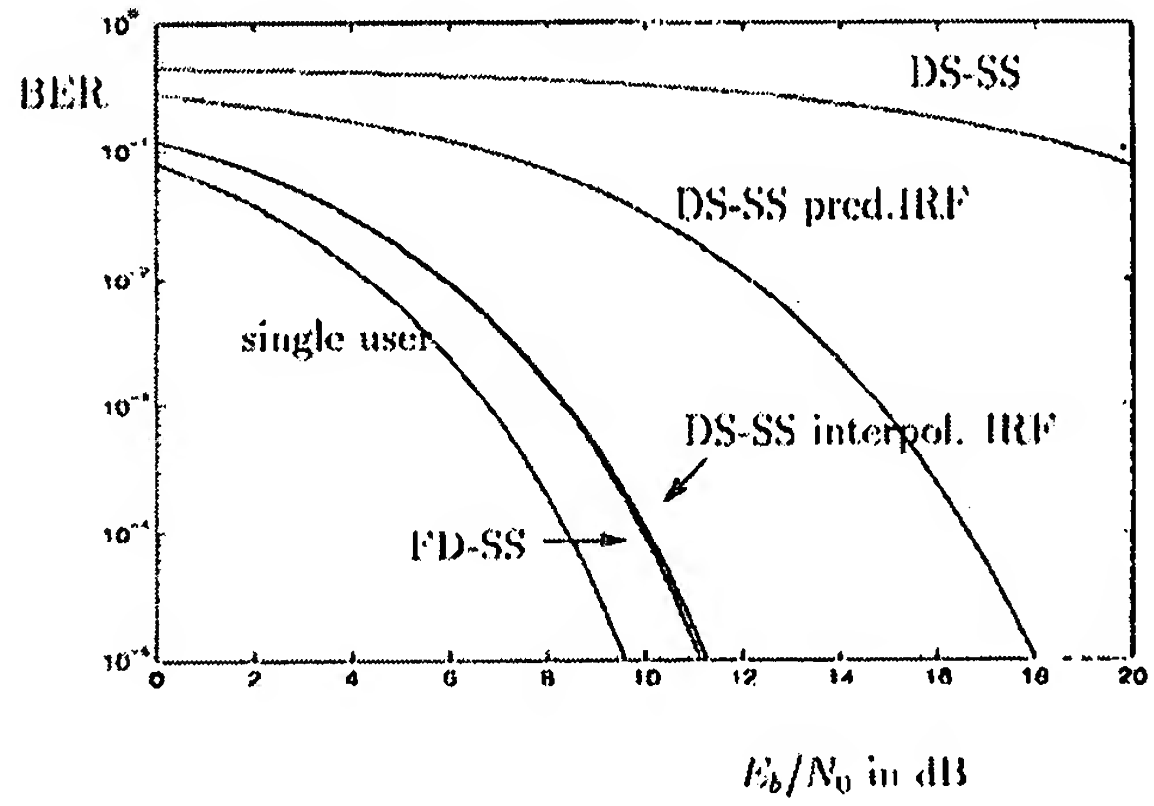

Fig. 2. Bit error rate (BER) for wide-band users in presence of narrow-band emissions employing different transmissions schemes ($\eta = 1/3$, narrow-band $J_0/N_0 = 25$ dB, and $L = 256$).

D. Comparison

In Fig. 2, we compare the bit error probability as a function of E_b/N_0 for the two wide-band modulation schemes employing QPSK symbols in a typical coexistence scenario. We assume that narrow-band emissions with typically high $J_0/N_0 = 25$ dB exist in one third of the frequency band. The figure indicates that the FD-SS transmission scheme offers an E_b/N_0 advantage of 5 dB over the DS-SS transmission scheme with prediction IRF at a bit error probability of 10^{-3}. Using the bound for an interpolation IRF, there is no significant performance advantage for the FD-SS scheme as we expect from our comparison above and the spreading factor of $L = 256$. However, as stated above, it might not be easy to realize a filter with a sufficient number of coefficients to approach the theoretical bound.

V. Overlay System Capacity

Any reduction in transmitting power needed per wide-band user to coexist with narrow-band emissions translates into less interference for the fixed narrow-band users. Given a maximum admitted degradation of the narrow-band transmissions' performance, this reduction is converted into an increased number of tolerable wide-band overlay users and thus increased capacity. In this section, we show this capacity advantage and the possible tradeoff between the number of wide-band and narrow-band users coexisting in the frequency band. For the capacity evaluation, cellular issues like frequency reuse, voice activity, and sectorization are not considered here.

Three different scenarios are considered:

- the case of narrow-band users occupying permanently a fixed fraction η of the frequency band;
- the case of suppressing the transmission of FD-SS replicas on subchannels occupied by narrow-band users;
- the case of narrow-band statistically independent transmissions appearing randomly in every subchannel with a probability p.

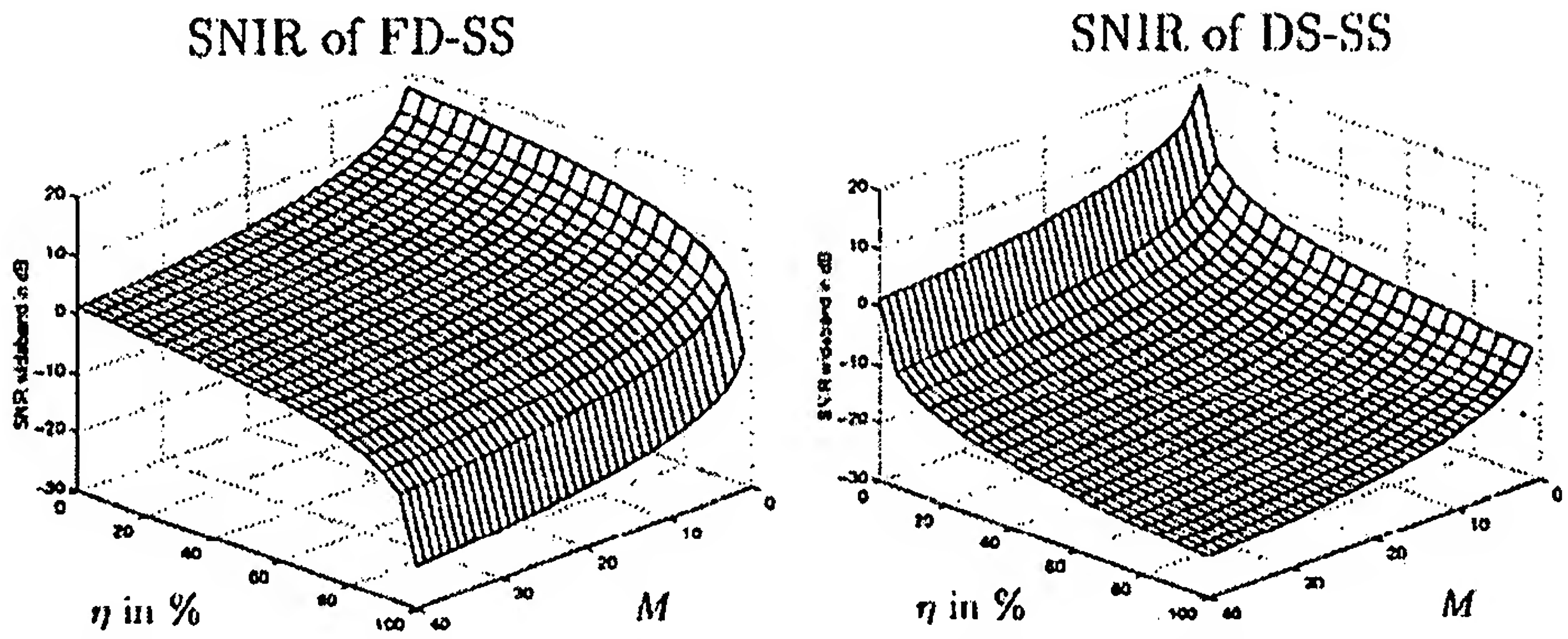

Fig. 3. SNIR for wide-band users employing the FD-SS and the conventional DS-SS scheme. The SNIR is shown as a function of the spectral occupancy by narrow-band emissions η and of the total number of wide-band overlay users M ($L = 256$, max. narrow-band SNIR degradation of 1 dB, and narrow-band $E_s/N_0 = 25$ dB).

A. Permanent Users in Fraction η of the Frequency Band

We show the capacity advantage and the possible tradeoff between the number M of wide-band users and NBS's coexisting in a fraction η of the frequency band. We assume NBS's with a typical signal to noise ratio of

$$\gamma_N = J_0/N_0 = 25 \text{ dB}$$

which is not to be degraded by the overlay users by more than 1 dB. This is equivalent to

$$1 \geq \beta_N > \beta_{N,\min} = 10^{-1/10}.$$

With (12), this is a relation between the number of overlay users M and the maximum E_s/N_0 admissible. The SNIR for both FD-SS and DS-SS receivers is calculated and traced in Fig. 3 as a function of M, the number of active wide-band users, and as a function of η, the fraction of bandwidth occupied by the narrow-band users. For $\eta = 0$ and 1, the two surfaces have identical values representing the case of no and uniform interference over the whole frequency band, respectively. Both receivers' SNIR's show a convex behavior with respect to the number of coexisting wide-band users M. However, the FD-SS receiver's SNIR is concave with respect to the narrow-band interference η showing a good resistance up to high values of η, whereas the DS-SS receiver's SNIR is convex and drops rapidly already at small values of η. The surfaces for DS-SS receivers with interference rejection filters lie in between these two surfaces having always better SNIR than the DS-SS and always worse SNIR than the FD-SS schemes. The SNIR of the DS-SS detector with interpolating IRF almost coincides with the one for the FD-SS detector, but the result for the IRF DS-SS scheme is an upper bound attainable only with an infinite length of the IRF, whereas the FD-SS only requires a combiner which weighs and sums the replicas according to their reliability in order to counter the narrow-band interference.

Fig. 4 shows the possible tradeoff between narrow-band and wide-band usage of the frequency band. Assuming for the wide-band receiver a minimum SNIR ($\text{SNIR}_{\min}$) of 5 dB, we show contour plots, i.e., intersections of the SNIR surfaces and a plane at $\text{SNIR}_{\min}$. The area to the lower left of the curves shows parameter combinations for which reliable

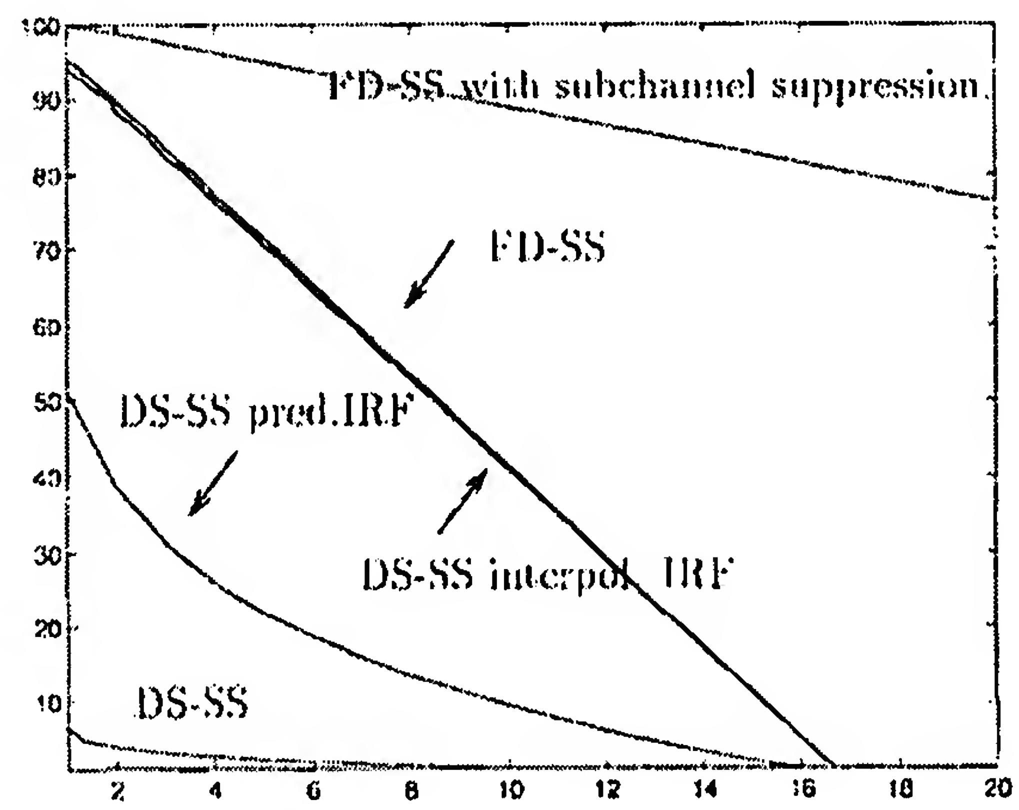

Fig. 4. Possible tradeoff between presence of narrow-band emissions in a fraction of the frequency band η and the number of wide-band overlay users M employing the FD-SS, FD-SS with subchannel suppression, DS-SS with predicting or interpolating IRF, and conventional DS-SS scheme (max. narrow-band SNIR degradation of 1 dB, $\text{SNIR}_{\min} = 5$ dB, $L = 256$, and narrow-band $E_s/N_0 = 25$ dB).

transmission is possible. The results show the superiority of the FD-SS transmission scheme over a spread-spectrum overlay system with a predictor-type IRF. Recall that both types of interference rejection filters are harder to implement than the FD-SS receiver.

B. Suppressing Transmission of Replicas in Occupied Subchannels

The information-theoretic water-pouring principle [17] suggests to avoid transmitting signals over subchannels occupied by strong interferers. The use of notch filters in the DS-SS system [2] is a way to apply this principle. However, while the DS-SS signal suffers from distortion by the notch filters, the FD-SS signal has the advantage of applying naturally the water-pouring principle; the transmission of replicas on subchannels occupied by narrow-band users can simply be omitted if the corresponding side information is available at the transmitter. With this facility, mutual interference between wide-band and NBS's is completely suppressed. The degradation of the wide-band users' performance results now only

from the interference of the other SS users and from the reduction of the available bandwidth by a factor of η

$$\mathrm{SNIR} = \frac{E_s}{N_0}\frac{1}{1+\frac{M-1}{(1-\eta)L}\frac{E_s}{N_0}}. \tag{20}$$

Neglecting the thermal noise, the maximum number of wide-band users is

$$M = \frac{(1-\eta)L}{\mathrm{SNIR}_{\min}} + 1 \tag{21}$$

where $\mathrm{SNIR}_{\min}$ is the minimum SNIR that guarantees a reliable transmission. This relation is shown in Fig. 4 by the curve designated by FD-SS with subchannel suppression. Since there is no restriction on the power of the overlay users with this transmission system, the capacity largely exceeds those of the other schemes.

C. *Independent Random Narrow-Band Signaling in Each Subchannel*

This second scenario corresponds to the case of an overlay over a frequency band occupied by a frequency division multiple access system, where the different channels become active independently with probability p. The performance measure is then the outage probability P_{out} for the wide-band overlay transmission system. The outage probability is the probability that the bit error probability is larger than a predetermined threshold. This is also the probability that the wide-band users' SNIR falls below the minimum necessary value $\mathrm{SNIR}_{\min}$: $P_{\text{out}} = \mathrm{Prob}[\mathrm{SNIR} < \mathrm{SNIR}_{\min}]$.

The SNIR in the FD-SS receiver is a function of the random variable l, the number of active narrow-band users. We have

$$\mathrm{SNIR}(l) = \frac{E_s}{N_0}\left(\frac{\frac{l}{L}}{1+\frac{M-1}{L}\frac{E_s}{N_0}+\frac{J_0}{N_0}} + \frac{\frac{L-l}{L}}{1+\frac{M-1}{L}\frac{E_s}{N_0}}\right). \tag{22}$$

Notice that $\mathrm{SNIR}(l)$ is a monotonously decreasing function of l. Let l' be the smallest l for which $\mathrm{SNIR}(l)$ is smaller than $\mathrm{SNIR}_{\min}$, i.e.,

$$\text{with } l' = \left\lceil \left[\mathrm{SNIR}_{\min}\frac{N_0}{E_s}L - \frac{L}{1+c}\right]\frac{(1+c+d)(1+c)}{d}\right\rceil$$
$$c = \frac{M-1}{L}\frac{E_s}{N_0} \quad d = \frac{J_0}{N_0}$$

where $\lceil x \rceil$ denotes the smallest integer larger or equal to x. The outage probability is then the probability that the number of active narrow-band users is larger or equal to l', i.e.,

$$P_{\text{out}} = \sum_{l=l'}^{L}\binom{L}{l}p^l(1-p)^{L-l}. \tag{23}$$

Similarly, the SNIR in the DS-SS receiver with predictor IRF is a decreasing function of l

$$\mathrm{SNIR}(l) = \frac{E_s}{N_0}\frac{a+b}{(1+b)^{1-l/L}\left(1+b+\frac{a}{l/L}\right)^{l/L}-1} \times\left(1+\frac{M-1}{L}\frac{E_s}{N_0}+\frac{l}{L}\frac{J_0}{N_0}\right)^{-1} \tag{24}$$

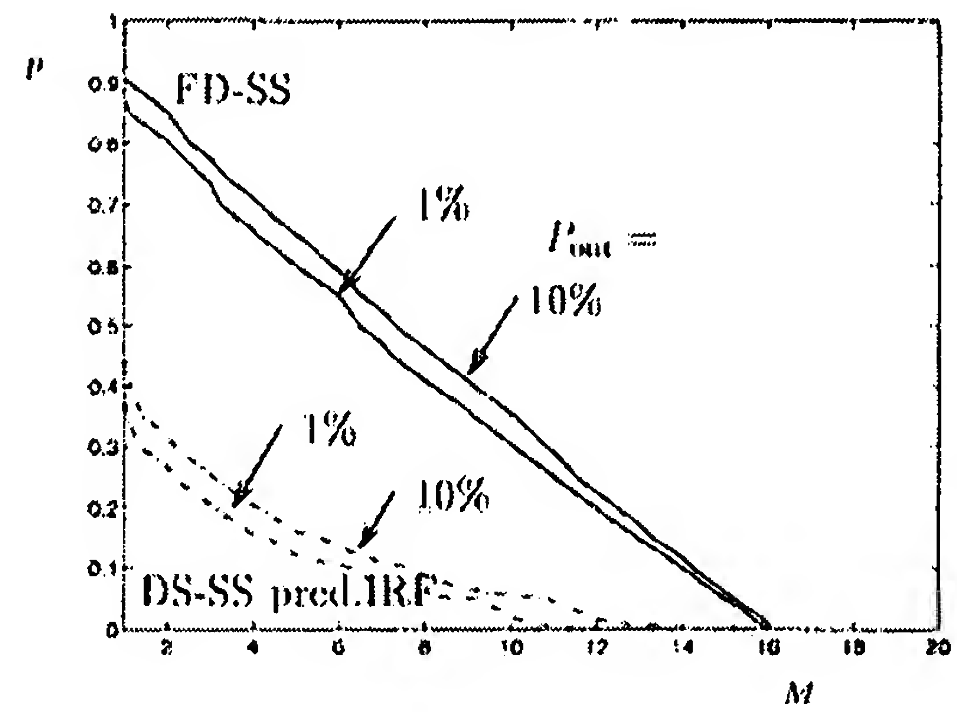

Fig. 5. Possible tradeoff between probability of active narrow-band emissions p and number of wide-band overlay users M employing the FD-SS and the DS-SS with predictor IRF for an outage probability of 1% and 10%, respectively (max. narrow-band SNIR degradation of 1 dB, $\mathrm{SNIR}_{\min} = 5$ dB, $L = 256$, and narrow-band $E_s/N_0 = 25$ dB).

with

$$a = \frac{J_0}{E_s}l \quad b = L\frac{N_0}{E_s} + M - 1.$$

The formula for the outage probability is obviously the same as in (23) above. The corresponding value for l' has to be found by a numerical search since there is no explicit expression as in the FD-SS available.

To compare the two transmission schemes, curves representing pairs of the narrow-band activity probability p and the number of wide-band overlay users M yielding an outage probability of 1% and 10% are shown in Fig. 5. Pairs lying to the lower left of the curves have lower outage probability. Again, the FD-SS scheme allows for more overlay users, i.e., higher capacity, than the DS-SS scheme with interference rejection filter.

The scenario under examination can be generalized to the case where the number of subchannels available for active narrow-band users is N, where N is smaller or equal to the number of subchannels L. Each one of the available N subchannels is occupied with a probability p. If $N < L$, the capacity for the wide-band overlay users is higher than in the previous case which corresponds to $N = L$. The outage probability for the FD-SS system is then

$$P_{\text{out}} = \sum_{l=l'}^{N}\binom{N}{l}p^l(1-p)^{N-l} \tag{25}$$

where l' is defined as above. If l' is greater than N, the sum in (25) is understood to be zero. Fig. 6 shows the tradeoff curves for the FD-SS receiver for different ratios of N/L. The ratio 1 corresponds to the previous example. Notice that for low N/L, the maximum overlay capacity, determined here by the maximum degradation of narrow-band SNIR of 1 dB, can be approached even for high values of the probability p.

VI. Multipath Channels

Like the DS-SS system, the FD-SS system is inherently resistant to slowly time-varying frequency-selective fading. If the channel's coherence bandwidth is much greater than the

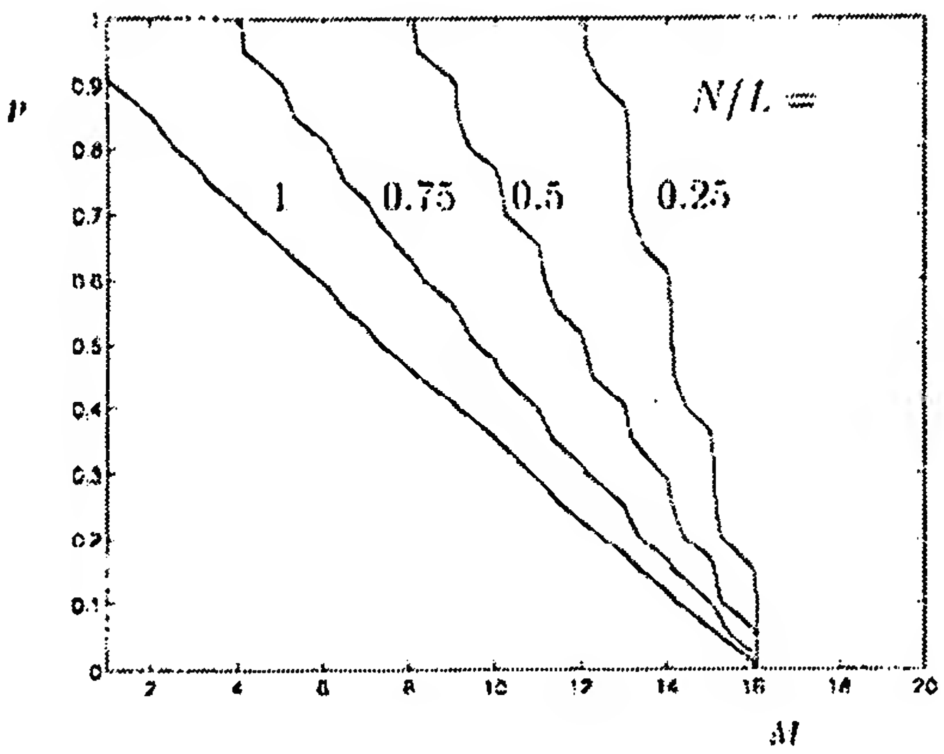

Fig. 6. Possible tradeoff between probability of active narrow-band emissions p and number of wide-band overlay users M with relative narrow-band user population N/L of 1, 0.75, 0.5, and 0.25 (P_{out} = 10%, max. narrow-band SNIR degradation of 1 dB, $\mathrm{SNIR}_{min} = 5$ dB, $L = 256$, and narrow-band $E_s/N_0 = 25$ dB).

bandwidth of a subchannel each subchannel will be affected by flat fading. Then, the expression of the matched filter outputs of (13) becomes

$$r_{m,il} = \frac{\sqrt{2E_s}}{L} a_{m,i} c_{m,il} \alpha_{m,l} + j_{il} + n_{il}. \tag{26}$$

If the receiver has side information about the corresponding complex attenuation $\alpha_{m,l}$ on the lth subchannel, the decision variable for optimum reception computes as

$$U_{m,i} = \sum_{l \in \mathcal{J}} \frac{r_{m,il} c^*_{m,il} \alpha^*_{m,l}}{\sigma_j^2 + \sigma_n^2} + \sum_{l \in \mathcal{S}} \frac{r_{m,il} c^*_{m,il} \alpha^*_{m,l}}{\sigma_n^2}. \tag{27}$$

Therefore, with a simple change in the computation of the combiner weights the matched filter for the FD-SS waveform over the multipath channel is realized. The presence of strong narrow-band interference or a deep fade of the channel are treated equivalently by the FD-SS receiver. The implementation of the matched filtering in the DS-SS receiver is made via the RAKE filter which represents an additional correlator or a tapped delay line with a subsequent combiner. Neglecting the channel and interference estimation problem, the DS-SS receiver with interference rejection and RAKE combining has a higher conceptual complexity than the FD-SS receiver.

VII. Conclusion

SS CDMA is a means to share the spectrum with existing narrow-band users. This procedure is limited by the amount of additional interference permitted for the narrow-band users. In this paper, we have shown that the frequency-diversity SS modulation scheme is considerably more resistant against partial-band interference than DS-SS with predictor-type interference rejection filters. It performs also slightly better with respect to the use of the optimal and complicated interpolation rejector. So more overlay users can be "layered" over the existing narrow-band users. Moreover, the frequency-diversity SS receiver is conceptually simpler than its DS-SS counterpart with interference rejection filtering.

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THE CAPACITY OF BROADBAND CDMA OVERLAYING A GSM CELLULAR SYSTEM

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1. Introduction

Code Division Multiple Access (CDMA) using direct-sequence spread spectrum (DS-SS) has been adopted as a method to provide digital cellular telephony in the U.S. [1]. The approach codified in TIA IS-95 uses a relatively narrow bandwidth of 1.25 MHz. This requires the use of an 8 kbps vocoder which provides less than toll quality speech service and cannot support G3 fax voiceband modems. It also necessitates displacing AMPS service by vacating frequency channels occupied by CDMA channels both in the home cell as well as those two cells away [2], [3].

An alternate approach, the Broadband-CDMA Overlay, has been proposed for North American cellular [4]. This technique uses a 10 MHz Broadband-CDMA (B-CDMA) signal which spreads over the entire contiguous bands A or B, leaving the extended bands for AMPS alone. The B-CDMA Overlay does not require displacing any AMPS users. Instead it uses a combination of broadband DS-SS along with agile receive and transmit notch filtering at the base station to cohabitate the same spectrum used by the AMPS service. By this technique a significant increase in capacity can be realized [5], [6]. A successful demonstration of this concept has recently been conducted with U.S. Cellular in Des Moines, Iowa.

Clearly, the B-CDMA Overlay concept can also be applied to any relatively narrowband TDMA cellular system such as IS-54 or GSM. This paper addresses the issue of the likely capacity improvement that can be achieved through B-CDMA Overlay of GSM. A comparison of GSM and a B-CDMA Overlay technical characteristics is given in Table 1.

Table 1. Comparison of GSM and B-CDMA Overlay

PARAMETERS	GSM*	B-CDMA
Channel Access	FDMA/TDMA	DS-SS CDMA
Modulation	GMSK	DQPSK
Data rate before FEC (kpbs)	8 X 13	16
FEC rate	½**	½
Data rate after FEC (kbps)	8 x 22.8	32
Modulation data rate per channel with overhead (kbps)	270.8	32
Required CIR (dB)	9 (> 90%)	4.5(rev)/3.5(for)
Spread bandwidth (MHz)	.	6
Handheld ERP (w)	2	TBD
RF Channels per sector	≤ 3	TBD
Trunks per sector	≤ 24	TBD

* ETSI/GSM Recommendation 05.01, Version 3.3.1, "Physical Layer on the Radio Path: General Description," January 1990.

** Class 1 only.

2. The B-CDMA Overlay Concept

The B-CDMA mobiles are dual mode with GSM and are given a B-CDMA channel when available in preference to a GSM channel. The B-CDMA base station is assumed to be collocated with the GSM base and to share antennas. The total interference power received by the GSM base from B-CDMA mobiles, including spillover from other neighboring cells, is controlled at a level sufficiently below the power received from the weakest GSM mobile to cause only a small, acceptable degradation in carrier-to-interference ratio. This is depicted in Figure 1(a). The B-CDMA base places notch filters at frequencies corresponding to the strongest GSM mobiles received

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by the B-CDMA base, as shown in Figure 1(b). The total notch width is maintained at an acceptable level. Those residual GSM signals not filtered as shown in Figure 1(c) are suppressed by the spread spectrum processing gain.

For the forward link (downlink) the base station uses transmit notch filters at the same frequencies used for received notches, under the assumption that those mobiles are the closest and hence, most susceptible to interference from the B-CDMA base. This is shown in Figure 2. Note that a GSM base may receive interference from a more distant B-CDMA base. The unnotched B-CDMA transmit power must be high enough to overcome the total GSM transmit power, at the B-CDMA mobile, as well as any additional interference from other GSM and all B-CDMA bases, after de-spreading the desired B-CDMA signal.

3. B-CDMA Overall Capacity

In order to estimate the capacity of the B-CDMA overlay it is necessary to ensure that signals are received with sufficient CIR by both the B-CDMA and GSM bases and mobiles.

3.A B-CDMA Mobile Interference to GSM Base

DS-SS CDMA systems are designed to have nearly ideal reverse link (uplink) power control in order to maximize system capacity. Thus all CDMA mobiles in a cell or sector will provide approximately equal interference to the GSM base. There is additional CDMA interference from surrounding cells. This spillover power ratio, i, has been found by simulation to be about 60% of the local cell interference for omni cells and about 85% of the local sector interference for three-sector cells [7]. The CDMA interference is reduced by the bandwidth dilution K = W/B, where W is the spread bandwidth (6 MHz) and B is the GSM bandwidth (270.8 KHz), so that K = 13.5 dB. If voice activity detection is employed then the interference power is further reduced by a, the average channel activity factor. In the B-CDMA case a = 0.625 including overhead. Taken together the total average B-CDMA interference to the GSM base is

$$I_c = a(1 + i)\, N P_c / K \tag{1}$$

for N B-CDMA mobiles per sector with receive power controlled to P_C.

The GSM mobile is designed to operate with at least a 9 dB CIR. The co-channel interference due to the GSM mobiles using the same frequency channel was estimated by simulation. The parameters used are in Table 2. The simulation uses hexagonal cells with three 120 degree sectors in each cell (see Figure 3). Mobiles are randomly uniformly distributed over the sector. (For the GSM simulations all mobiles using one of the three channels are collocated for purposes of simplicity.) Each mobile has its transmit power adjusted according to the GSM power control algorithm with a -66 dBm set point.

The propagation model assumes R^{-2} loss before and R^{-4} loss after a breakpoint given by 4 H_t H_r/λ, where H_t and H_r are the transmit and receive antenna heights, selected to be 1.5m and 20 m, respectively. Additionally there is a random shadow loss (or gain) given by a log-normal distribution with an 8 dB standard deviation.

Figure 4 depicts the cumulative probability of the power received at the base for four cases:

(1) Individual mobiles - the power received from individual mobiles in the GSM home sector.

(2) Total All Mobiles - the combined power received from GSM mobiles in all sectors.

(3) With 9 Notches - the total GSM mobile power received by a collocated CDMA base after filtering with nine agile notch filters (each filter has 35 dB rejection).

(4) Co-Channel Interference - the total interference power from mobiles in all other sectors using the same frequencies as in the home sector.

A four - cell frequency reuse pattern is assumed (see Figure 3). The 10th percentile GSM mobile is received with a power of -70 dBm. At that level the average C/I_G due to GSM Co-Channel interference is 22.1 dB. Therefore, the CDMA interference must provide a C/I_C of 9.2 dB to result in an overall C/I of 9 dB.

Table 2. GSM Simulation Model

- Hexagonal cells, 4 frequency reuse
- 3 sectors per cell
- 1 to 3 channels per sector @ 100% load
- Cell radius = 1 km
- Antenna height = 20 m
- Base antenna gain = 6 dB
- Antenna front/back = 20 dB
- Mobile ERP = 2 W
- GSM power control set point = -66 dBm
- Log - normal shadow loss with 8 dB standard deviation

Let $P_{GSM}/I_c \geq$ required SNR = 9.2 dB. Then, using (1) $10 \log I_c = -70$ dBm - 9.2 dB = -79.2 dBm.

3.B GSM and B-CDMA Mobile Interference to B-CDMA Base

Call Γ_c the required E_b/N_o for the B-CDMA reverse link, which is 4 dB. With notch filters each of bandwidth B, the effective spread bandwidth is reduced by $F = B\, n_f$. Thus

$$\Gamma_c = G\,(1-F)\, P_c \Big/ \left((\alpha N - 1 + j M)\, P_c + \frac{P_f}{1-F} \right) \qquad (2)$$

where G = processing gain without notches
= $W/f_{B\text{-}CDMA}$ = 6 MHz/16 kbps
= 25.7 dB

and P_f = residual GSM interference power after base notch filtering.

Call I_o = $K I_c + P_f/(1-F)$, the total effective interference. From Figure 4 we find that the median P_f = -71 dBm for the case of 2 RF channels in use. Using (1) and (2) we can solve for P_C as

$$P_c = I_o / (\alpha + G\,(1-F)/\Gamma_c) \qquad (3)$$

and obtain N from

$$N = I_c / \alpha\, (1+f)\, P_c \qquad (4)$$

Using the values from above yields P_C = -83 dBm and N = 46 per sector.

Therefore, the B-CDMA Reverse Link cell capacity is 3N = 153 when GSM system is loaded to nominal conditions, i.e., approximately ⅔ occupied.

Table 3 summarizes the overlay uplink capacity as a function of GSM load, with and without notch filters. Note that at nominal ⅔ GSM loading the B-CDMA overlay can nearly quadruple the total traffic with notch filters, and almost triple it even without filters. It is also worth noting that the B-CDMA mobiles are transmitting with about 16 dB lower power than the median GSM mobile.

Table 3. Summary of B-CDMA Overlay Uplink versus GSM Loading

Number of Active GSM Channels/Sector	GSM Traffic (8 Users/Channel)	B-CDMA Overlay Uplink Traffic Per Sector		Capacity Increase Over GSM	
		No. Notches	# Notches	No. Notches	# Notches
0	0	115	N/A	N/A	N/A
1	8	45	64	5.6	8.0
2	16	29	46	1.8	2.9
3	24	21	32	0.9	1.3

3.C Forward Link Capacity

The downlink is generally assumed to have a higher capacity than the uplink because the base can transmit with higher power and because it does not suffer the variations in power control as does the uplink. In our analysis we first consider the B-CDMA downlink and determine the minimum ratio of B-CDMA to GSM transmit power needed to support the uplink capacity. Then we determine whether the GSM downlink is adequate.

The received E_b/N_0 for the B-CDMA mobile is Γ_{CM} given by

$$\Gamma_{CM} = \frac{G\,(1-F)\,P_{CB}}{J\left[\alpha N_{CB} + (1-F)/\Gamma_{CM} - j\alpha M\right]} \qquad (5)$$

If we substitute previously used parameters for the case of M = 2 GSM channels per sector, where N = 46 B-CDMA channels per sector was determined for the uplink and assuming that j = 2 is a reasonable upper bound on total base interference, then P_{CB}/P_{GB} = -12.5 Db. This value becomes -12.2 dB for the case of a fully loaded GSM sector.

These lower values of B-CDMA transmit power would reduce the maximum cell size, even taking into account the 5.5 dB advantage in required CIR of the B-CDMA overlay. However, it will be shown below that higher B-CDMA transmit power can be used and still not cause interference to the GSM mobiles due to the transmit notch filters.

Next, we determine the GSM mobile CIR due to B-CDMA interference and GSM co-channel interference. For the former, we assume that the B-CDMA base average transmit power is aNP_{CB}, which is further suppressed by γ due to notch filtering or to excess propagation loss. (The assumption is that if the GSM mobile is received strongly by the B-CDMA base it would be notch filtered due to reciprocity.) The GSM mobile CIR, Γ_{GM}, it now given by

$$\Gamma_{GM} = \frac{P_{GB}}{\gamma aNP_{CB}/K + P_{GG}} \tag{6}$$

where P_{GG} is the GSM base co-channel interference power. In order to maintain an adequate CIR requires that

$$\gamma P_{CB}/P_{GB} \leq K\left(\Gamma_{GM}^{-1} - P_{GG}/P_{GB}\right)/aN \tag{7}$$

Using the previously determined value for P_{CB}/P_{GB} yields $\gamma \leq 0.82$. Therefore, transmit notch filter depths of 20 dB should be more than adequate to suppress B-CDMA base station interference to GSM mobiles and allow the B-CDMA base transmit power to be increased enough to support the GSM cell radius.

4. Summary and Conclusions

We have proposed that one can overlay an existing GSM cellular network with a broadband CDMA cellular system utilizing direct-sequence spread spectrum along with agile notch filters at the base station. Notch filter depths of 35 dB on receive and 20 dB in transmit were found to be adequate. Capacity calculations show that the B-CDMA overlay can approximately quadruple the nominal capacity of GSM, which is 16 channels per sector, by providing an additional 51 voice channels at 16 kbps each. Also, we have calculated that the B-CDMA mobile transmits on average with 16 dB less power than the GSM mobile, while the CDMA base transmit power per channel would be about 5.5 dB less than the GSM base due to the lower CIR required by the B-CDMA Overlay system.

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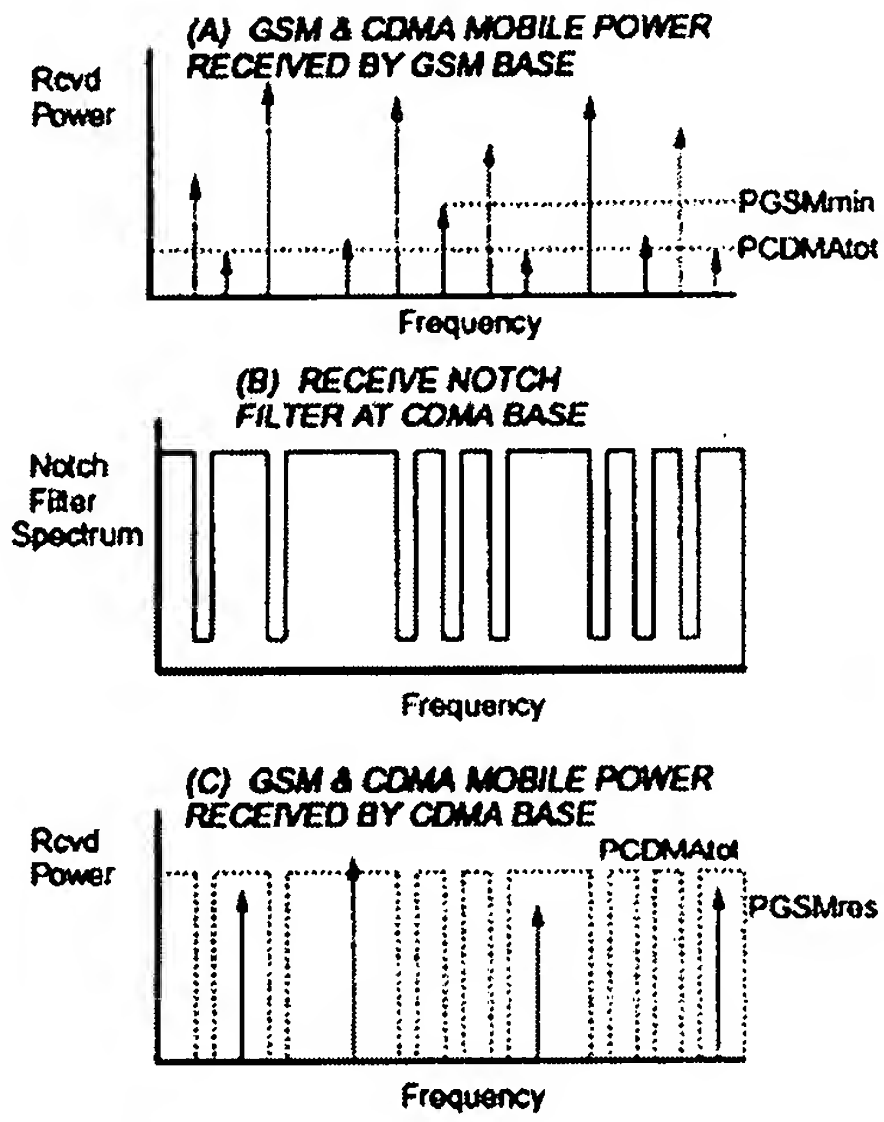

Fig.1. Use of Receive Notch Filters in GSM B-CDMA Overlay

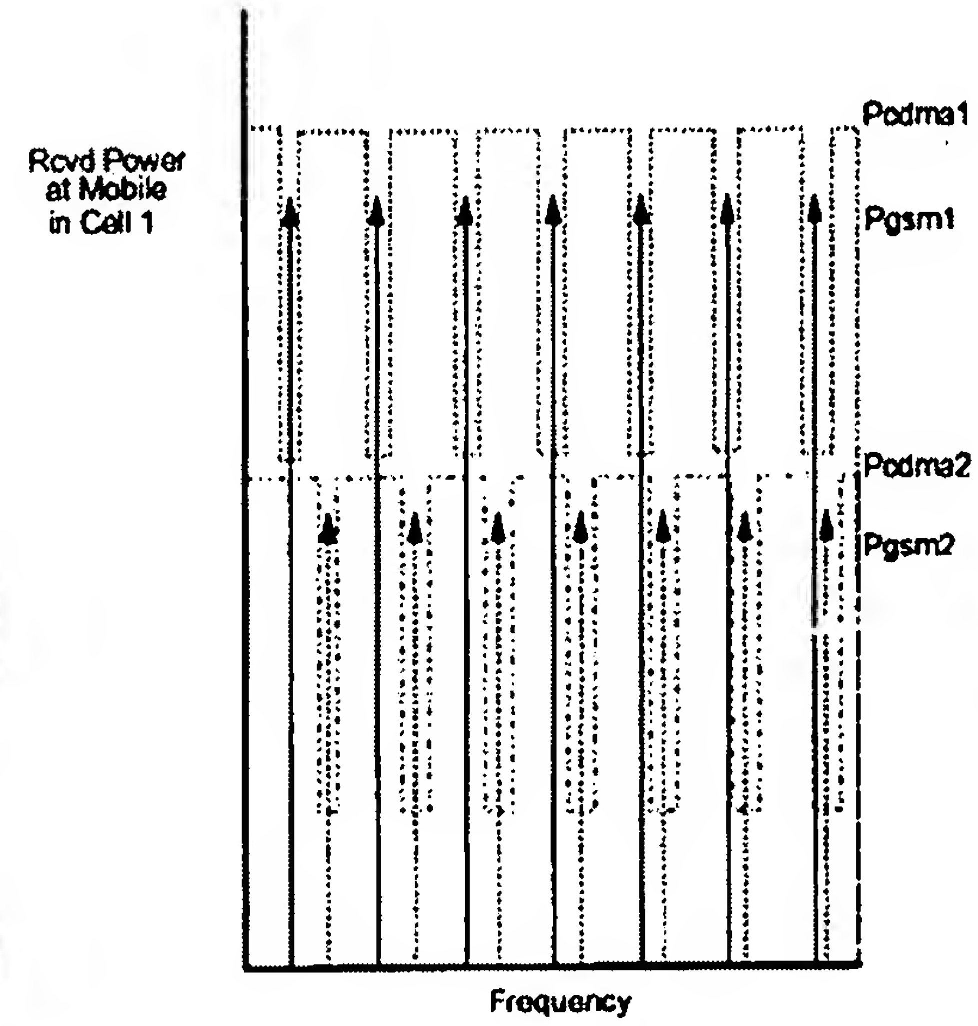

Fig.2. GSM & CDMA POWER RECEIVED BY MOBILE WITH CDMA BASE TRANSMIT NOTCH FILTERS

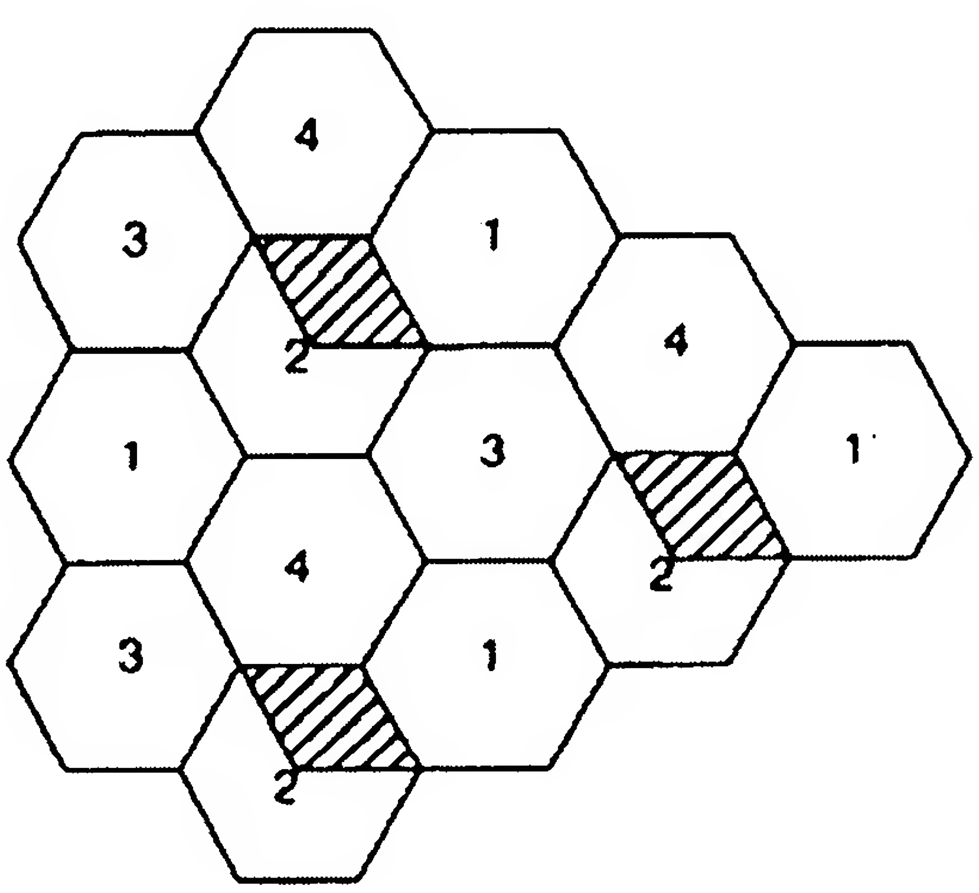

Figure 3. Sectored Cells with K = 4 Frequency Reuse Pattern

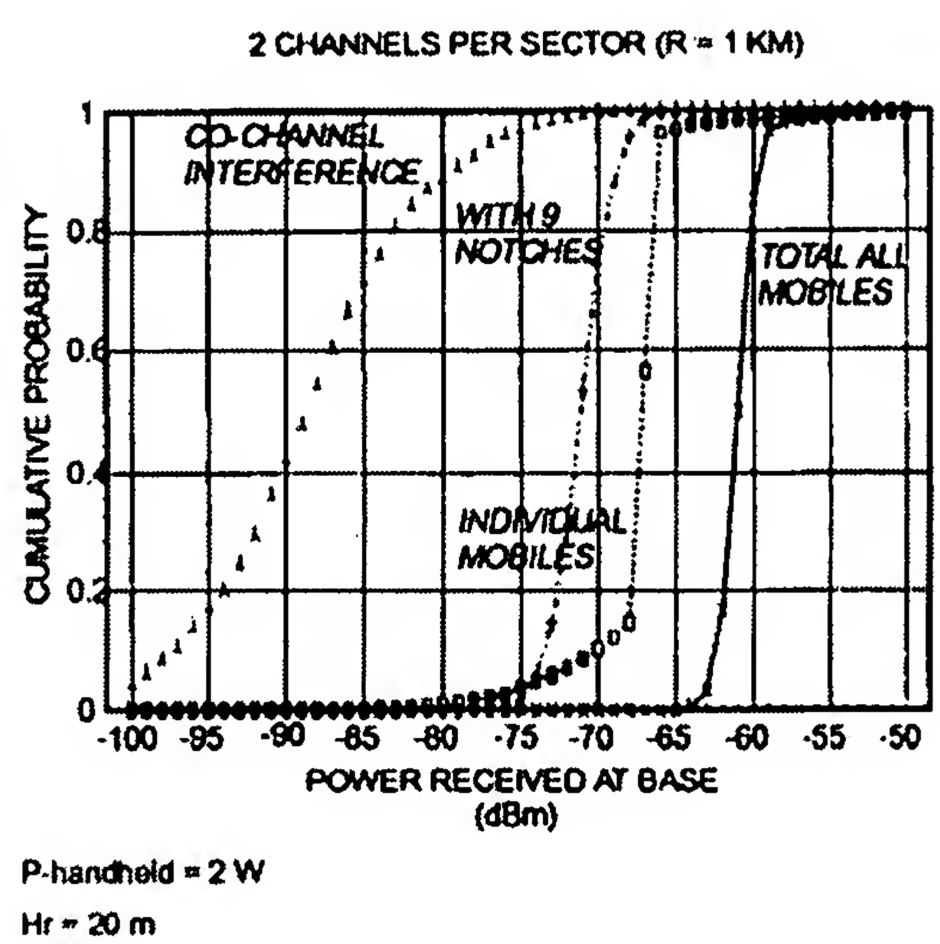

Fig.4 Power Received at GSM Base

Multicarrier CDMA for Cellular Overlay Systems

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***Abstract*— In this paper, a code-division multiple access (CDMA) cellular overlay system is investigated, employing the idea of multicarrier CDMA, which has recently received significant attention as an alternative to traditional single-carrier CDMA [1]. Overlay is pursued here as a means of long-term transition from narrowband cellular to CDMA cellular. A major result of this paper is the demonstration that the use of multicarrier CDMA in a fading channel is particularly beneficial to the narrowband system, as the CDMA users can reduce their transmitted powers as a result of diversity. Another significant conclusion is that the use of transmitter notching in the CDMA system in order to avoid active narrowband users outperforms a strategy in which a narrowband user is avoided by simply dropping the particular carrier which overlays it. Finally, recent results on the use of the minimum mean-squared error (MMSE) receiver in a fading channel are extended for use in the overlay scenario.**

***Index Terms*—Code-division multiple access (CDMA).**

I. INTRODUCTION

THE interest in code-division multiple access (CDMA) technology has been increasing dramatically, a trend that is likely to continue. In the future, CDMA will probably become the most widely used method of providing wireless service for products such as cellular phones. With a few exceptions, the current trends in cellular phones are almost exclusively frequency-division multiple access (FDMA) and time-division multiple access (TDMA). A transition to the day when CDMA is the dominant multiple-access method must occur gradually. The service providers cannot simply default on their commitments to the existing FDMA and TDMA subscribers. They could, however, begin to introduce the new CDMA units while halting the introduction of additional narrowband FDMA and TDMA units. In the long term, narrowband systems would be phased out gradually.

One possible way to make this transition is to employ CDMA overlay, in which a CDMA cellular system would be implemented in a frequency band which is dedicated to a narrowband cellular system [2], [3]. If the two systems are to coexist, they each must do so at loading levels, that is, the ratio of active users to the theoretical maximum number of users possible, which might be significantly below what it could be in an otherwise identical scenario without overlay. It will be the goal of this paper to examine exactly how many users of each type can be accommodated at different points, i.e., for different amounts of narrowband loading, in the long-term transition period.

Previously, the current authors showed for a single-cell system in [4] and for a cellular system in [5] [and both with an additive white Gaussian noise (AWGN) channel model] that the overlay of even a small number of CDMA users causes a significant amount of degradation to the existing narrowband system. It is possible that the number of supportable CDMA users would be so low that overlay might not be worthwhile. The use of notch filtering at the CDMA transmitters allows the CDMA signals to avoid the narrowband users' spectra and thus substantially reduces the effects of overlay on the narrowband system. The corresponding effect that this notching has on the CDMA system was shown to be minimal.

In this paper, those results will be extended to the fading channel. A brief description of the overlay system and the environment will be given in Section II. The number of CDMA users that can be supported is constrained by their effect on the narrowband users, which will be examined in Section III. Consistent with the results of [4] and [5], that number is quite small, and again, it can be improved substantially by employing notching in the CDMA transmitters. In Section IV, limits on the number of narrowband users that can be supported will be examined. Assuming that the CDMA users must employ some degree of notch filtering in order to achieve a respectable amount of loading, the number of narrowband users, in turn, is constrained because if there are many, the CDMA users might have to destroy a significant portion of their signals. These results will be combined with those of Section III to form joint capacity limits in terms of the number of CDMA and narrowband users that can be supported simultaneously. It will be seen that in traditional single-carrier CDMA, these limits are very constraining. With the use of multiple carriers, however, the added frequency diversity allows the CDMA users to transmit at lower powers with respect to the narrowband users, and hence they require less notching on the whole. The number of users that may share the channel is increased tremendously with multicarrier CDMA.

With these limits in mind, system simulations are performed in Section V to take into account CDMA performance, specifically in terms of bit error rate (BER). The effects of narrowband interference, multiaccess interference, notching, and the possibility of operating the multicarrier system on fewer carriers than the maximum will be looked at. Conclusions will be made in Section VI.

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II. Description of the System and Environment

In this section, a description of the cellular overlay system and the environment will be given. We consider a digital FDMA narrowband cellular system with a frequency reuse factor of 1/7, which means that the total system bandwidth will be divided into seven frequency groups, each consisting of a number of narrowband channels separated in frequency so as to minimize adjacent-channel interference. The groups are then assigned to the cells in an intelligent manner which minimizes the cochannel interference—that is, interference caused by mobiles in different cells using the same channel. The effects from mobiles in two outer layers of cells will be taken into account, with those users in the cells beyond neglected, as their signals should be sufficiently attenuated as a result of the propagation loss. The narrowband users will employ root-raised cosine pulse shaping in their transmitters, in order that the occupied bandwidth is $2/T_b$, where T_b is the bit time.

The CDMA system will be of a general multicarrier form, with M carriers. For the single carrier ($M = 1$) system, the processing gain will be taken as N chips/bit. For $M > 1$, the identical information for a given CDMA user will be transmitted on each of the M carriers, but with a different spreading code used for each carrier. The motivation for multicarrier CDMA is to use several carriers which are separated sufficiently in frequency so that the fading on signals sent on different carriers will be independent, thus affording diversity potential to the system.

In order to make fair comparisons of the different multicarrier systems in terms of bandwidth and power, the processing gain of each signal in the multicarrier case needs to be N/M, and the total power used by the CDMA user must be split equally among the M carriers. In order to compare the CDMA and narrowband systems, it will be assumed for simplicity that the two systems have the same information bit rate, and thus the CDMA signals will overlay N narrowband users. In the single-carrier case, these N users would occupy a contiguous frequency band, while for $M > 1$, the carriers must be separated in frequency, and thus the N narrowband users' spectra would occupy several disjoint frequency bands.

In this paper, the overlay will be done assuming that there is a great deal of coordination between the CDMA and narrowband systems. First of all, because the situation at hand involves a preexisting narrowband cellular system, many costly and permanent aspects of the overlay system, such as the base stations and the network interface to the wireline system, would already be operational. When the CDMA system is overlaid, it would be most cost efficient to implement it to utilize these elements. In this paper, we will consider an overlay system in which the two systems utilize the same base station layout, each placing an antenna on the same tower. The two systems also will be assumed to share a large amount of information, including knowledge of the received average power levels of the mobiles at each base station, the cell to which they are assigned, and the frequency locations of the narrowband mobiles.

A Rayleigh fading channel model will be used. In the single-carrier case, it will be assumed that the coherence bandwidth of the channel is on the order of the system bandwidth and therefore the signals undergo flat fading. Certainly then, each of the signals in the multicarrier case will undergo flat fading as well. In order to achieve diversity, the carriers must be sufficiently separated in frequency by an amount much greater than the coherence bandwidth in order that each undergo independent fading.

In addition to the fading, both the CDMA and the narrowband mobiles will undergo large-scale attenuation both from path loss with an exponent of n and from log-normal shadowing with a standard deviation of σ_g in dB. Throughout this paper, the values $n = 3$ and $\sigma_g = 8$ will be used.

Power control will be employed both by the narrowband system and by the CDMA system as a means of conserving battery life. In CDMA systems only, there is the additional motivation of alleviating the near–far problem among a system's own mobiles, so that one strong signal does not disrupt communication for all the rest. The mobiles will be assigned to that base station for which the composite path loss and shadowing is minimum, which might not be the closest one geographically. Its transmit power will then be set so that its signal arrives at the base station at a specified minimum value necessary for acceptable performance.

III. Limits on CDMA Capacity

In this section, a development of user capacity limits for an overlay scenario begins with a quantification of how many CDMA users can be tolerated by a typical narrowband system before its performance is degraded too severely. We will then look at the resulting improvement due to the CDMA users employing notch filtering in their transmitters.

We look at the performance of a binary phase shift keying (BPSK) user received in the presence of overlay in a fading channel. The general multicarrier CDMA system described in Section II will be used with M carriers, and the total power of each CDMA user divided equally among the M carriers. The fading process on each carrier will be taken as flat and independent of the fading processes on the other carriers.

It will be assumed that only the particular CDMA signal which overlays the BPSK signal at bandpass will pass through the BPSK receiver, and thus we will concentrate only on that signal in the equations which follow. The BPSK user employs root-raised cosine pulses with a rolloff factor of $\alpha = 0.35$ and a coherent matched-filter receiver. When the signal is received in the presence of fading and AWGN of spectral height $N_0/2$, the decision statistic out of the BPSK matched filter during the ith bit interval is given by [4]

$$Z(i) = \sqrt{2E_b}\gamma_b(i)d_b(i) + N(i) + \sum_{k=1}^{K}\sqrt{2P_k}MT_c\gamma_b(i)I_k(i) \qquad (1)$$

where E_b is the average energy-per-bit of the BPSK system, T_b is the bit time of both systems, T_c is the chip time for the single-carrier CDMA system, N is the composite processing gain, P_k is the kth CDMA user's composite average power from all M of the carriers, $\gamma_b(i)$ and $\gamma_k(i)$ are the BPSK

user's and kth CDMA user's fading process during the ith bit interval, with each a zero-mean complex Gaussian random variable, and $d_b(i)$ is the ith data bit of the BPSK user. The interference contribution associated with the kth CDMA user during the ith bit interval is given by

$$I_k(i) = \sum_{m=-L(N/M)}^{L(N/M)} \left[d_k\left(j + \left\lfloor \frac{m}{N/M} \right\rfloor\right) \times c_{k,\mathrm{mod}(m,N/M)} h(mMT_c - \tau_k) \right]. \tag{2}$$

In this expression, $d_k(i)$ is the ith data bit of the kth CDMA user, $\tau_k \in (0, T_b)$ is the kth CDMA user's delay, and K is the number of CDMA users. The kth user's spreading waveform $c_k(t)$ has a period of T_b and consists of N/M unit-amplitude square pulses of width MT_c. The quantity $c_{k,n} \in \{\pm 1\}$ is the nth chip of the kth user's spreading code. Also, the root-raised cosine pulse $h(t)$ is assumed negligible for $|t| > LT_b$.

Assuming coherent detection for the BPSK user, the decision on the ith data bit is given by $\hat{d}_b(i) = \mathrm{sign}(\mathrm{Re}(Z(i)\exp(-j\angle\gamma_b(i)))$. In the absence of overlay, the probability of bit error, conditioned on the BPSK user's fading process $\gamma_b(i)$, is

$$P(\text{error}/\gamma_b(i)) = Q\left(\sqrt{2\left(\frac{E_b}{N_0}\right)_b |\gamma_b(i)|^2}\right) \tag{3}$$

where $(E_b/N_0)_b$ has been clarified to apply to the BPSK user, not to be confused with that of the CDMA system, for which $(E_b/N_0)_c$ later will be used. Also, $Q(x)$ is the Gaussian Q-function. If this is further averaged over the Rayleigh probability density function (PDF) of the variable $|\gamma_b(i)|^2$, a well-known approximation for the probability of error is

$$P_e \approx \frac{0.25}{(E_b/N_0)_b}. \tag{4}$$

Thus, if a BER of 0.01 is desired in the absence of overlay, then $(E_b/N_0)_b = 14$ dB is required.

As mentioned before, it should be stipulated that the overlay causes only a minor amount of degradation to the existing narrowband system. A criterion to determine whether or not the overlay causes too much degradation to the BPSK system will now be given. If the BPSK user slightly raises its transmitted power by 1 dB such that $(E_b/N_0)_b = 15$ dB, then the number of CDMA users tolerable to the BPSK system will be that number for which the BPSK user, after the 1 dB power increase, still maintains an average BER of 0.01.

The capacity limits dictated by this criterion will be found for a system with a composite processing gain N of 32 chips/bit. It is intuitive that the results will not depend on the number of carriers used in the CDMA system. In a multicarrier system with $M > 1$ carriers, the CDMA signals on each carrier are only spread by a per-carrier processing gain of N/M, a smaller factor than in the single-carrier case. But in turn, the average power of the signal on each carrier is also reduced by a factor of M over the single-carrier case.

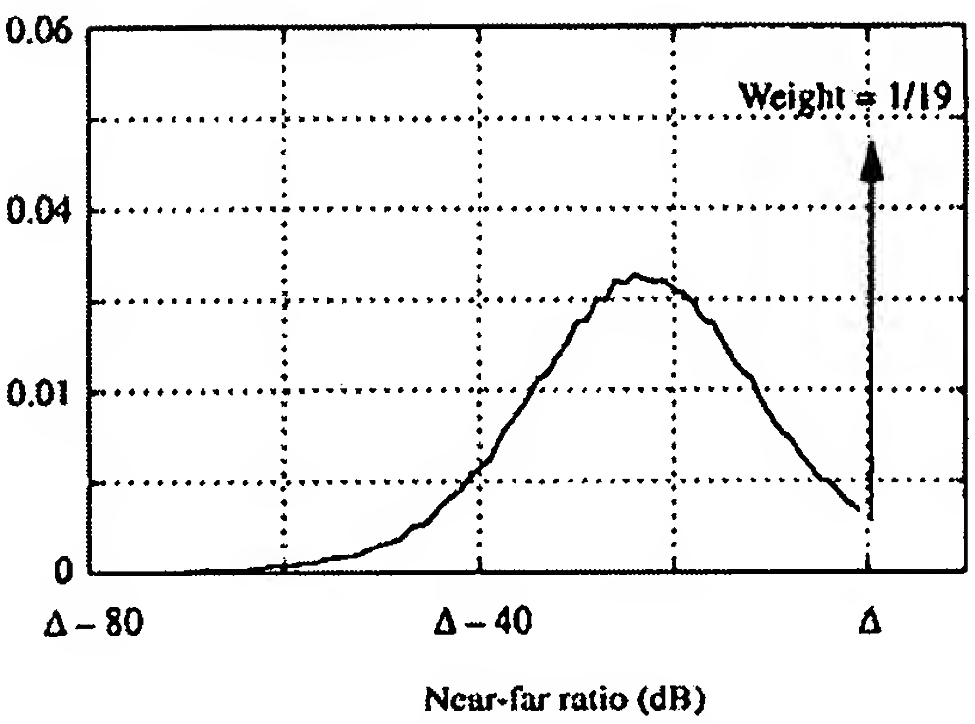

Fig. 1. Histogram of CDMA-to-BPSK near–far ratio, with $\Delta = (E_b/N_0)_b - (E_b/N_0)_c$. The system operates in an environment with a path-loss exponent of $n = 3$ and shadowing with a standard deviation of $\sigma_g = 8$ dB and uses power control.

A histogram of the CDMA-to-BPSK near–far ratio in dB units is shown in Fig. 1. This was obtained by generating a random location for a CDMA user and a shadowing process to each base station out of three layers of cells described earlier and then assigning it to that cell for which the composite path-loss and shadowing is minimized. Power control is then implemented so that it arrives at its assigned base station at a specified value. There is an impulse of weight 1/19 at the value $\Delta = (E_b/N_0)_b - (E_b/N_0)_c$, as the CDMA user has a probability of 1/19 of being assigned to the same cell as a narrowband user located in any given cell.

An important benefit of using a multicarrier format relates to the fact that the joint capacity limits of the system, in terms of both narrowband and CDMA capacity, depend on the difference $(E_b/N_0)_b - (E_b/N_0)_c$. In comparison to a single-carrier system, a multicarrier system with $M > 1$ can achieve the same BER with a smaller value of $(E_b/N_0)_c$, due to the added frequency diversity. The ability to operate the CDMA system at smaller values of $(E_b/N_0)_c$ greatly reduces its effect on the BPSK system and thus increases CDMA capacity in this regard.

Without the CDMA notching that has been mentioned, the amount of CDMA loading that the narrowband system can tolerate is practically zero. Thus, notch filtering will be used in the CDMA signals to avoid the BPSK user. To implement the notching, when a CDMA signal is received such that the BPSK user's received power is less than T dB above that CDMA signal, a notch is placed in the CDMA signal. The particular notch filtering method used in this paper will be based on the discrete Fourier transform (DFT), as described in [4].

In Fig. 2, for a range of values for the notching threshold T and several different fixed values of the difference $(E_b/N_0)_b - (E_b/N_0)_c$, the amount of CDMA loading tolerable to the BPSK user was found such that the previously described excess criterion was satisfied. As expected, for larger values of $(E_b/N_0)_b - (E_b/N_0)_c$, the PDF of the CDMA-to-BPSK near–far ratio (with the histogram given in Fig. 1) shifts toward lower values, and thus more CDMA users can be tolerated by the BPSK user. And as the notching threshold T increases, and

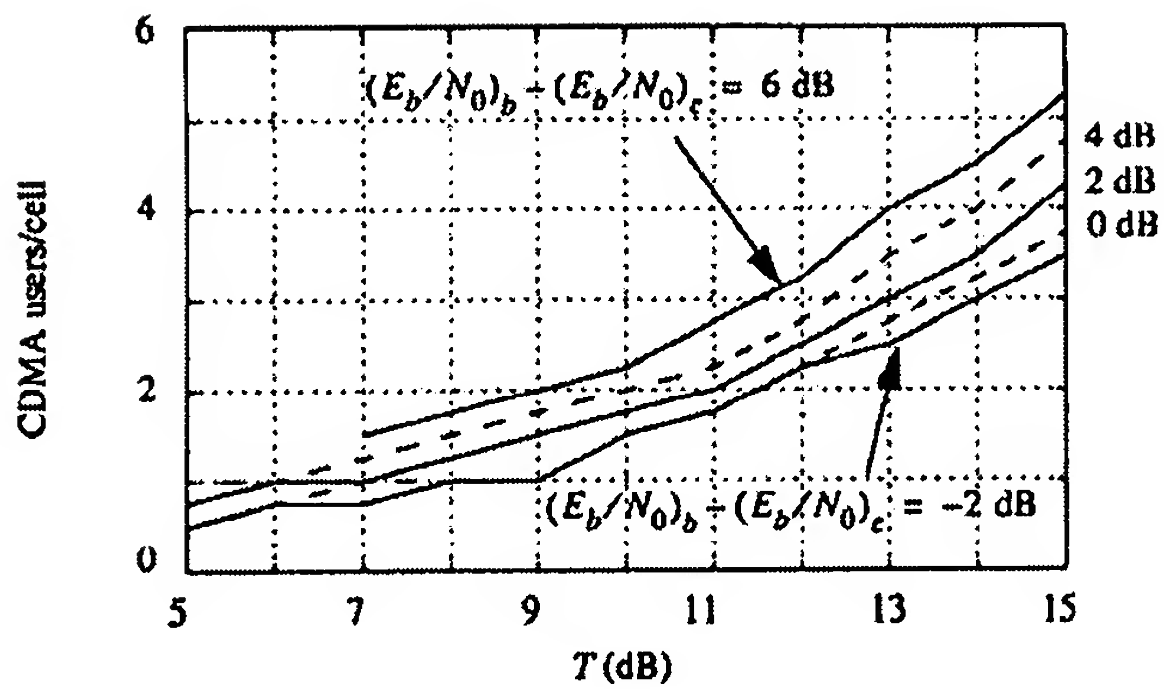

Fig. 2. CDMA users/cell tolerable to the BPSK system. Processing gain is 32 chips/bit. CDMA user is notched if BPSK power is less than T dB above CDMA power. Curves are for $(E_b/N_0)_b - (E_b/N_0)_c$ values of $6, 4, \ldots, -2$ dB. $(E_b/N_0)_b$ and $(E_b/N_0)_c$ represent values after power control at the base station to which the BPSK or CDMA mobile is assigned.

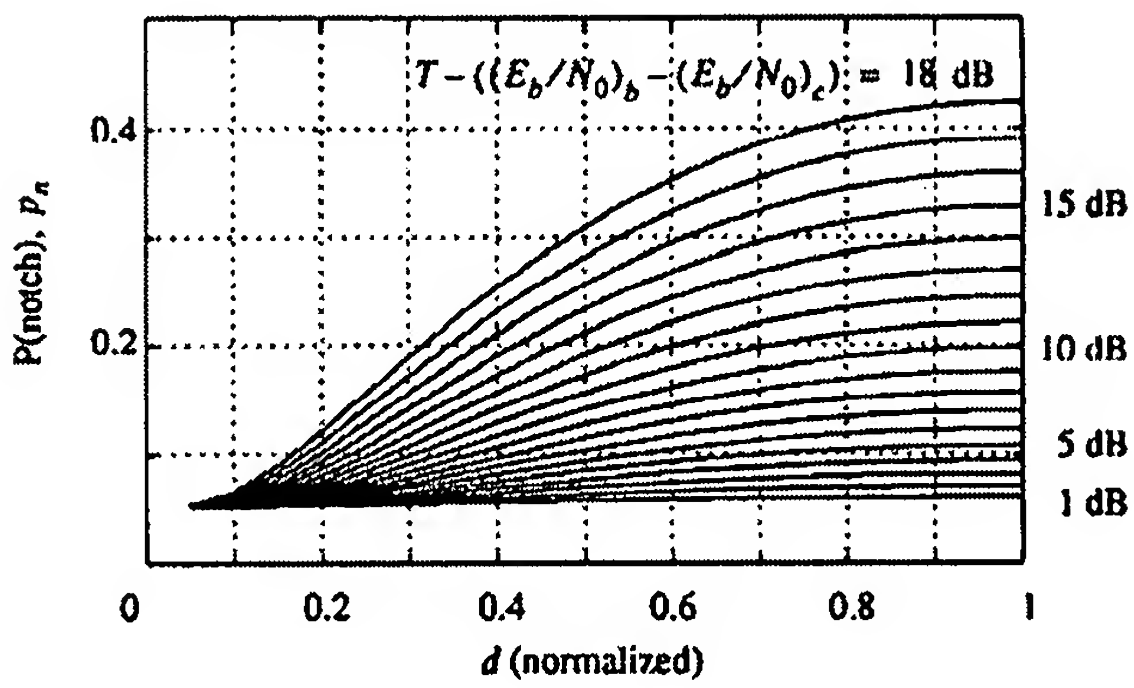

Fig. 3. Notching probability p_n for a narrowband user located at a normalized distance d from the closest base station, for different values of $T - ((E_b/N_0)_b - (E_b/N_0)_c)$ in dB.

the CDMA users are therefore more likely to place notches, the BPSK user also can tolerate more CDMA users. In order to make use of these results, we must next investigate how much notching the CDMA system can handle before its signals become too distorted to be received reliably.

IV. Limits on Narrowband Capacity

In this section, we will look at the effects of notching from the perspective of the CDMA system and find fundamental limits on the number of supportable narrowband users. As the narrowband loading increases, and hence more notches are necessary in the CDMA signals, there will be a point at which an excessive amount of some of the CDMA signals' spectra must be notched out. Therefore, many of the CDMA users would have to be dropped. This would occur not only in cases for which the notching threshold T is large, but would also occur when the quantity $(E_b/N_0)_b - (E_b/N_0)_c$ is decreased, or equivalently, if the value of $(E_b/N_0)_c$ is increased.

In [5], the following related problem was examined. Assume that a single narrowband user is located at random such that it is equally likely to be assigned to any of the cells within two outer layers of a center cell of interest. Then, consider a CDMA user located at a normalized distance $0 < d \leq 1$ from the center cell. The probability that the CDMA user must notch for that narrowband user p_n is plotted in Fig. 3 as a function of d. Each curve represents a different value of the quantity $T - ((E_b/N_0)_b - (E_b/N_0)_c)$. For a number of narrowband users located uniformly throughout these several layers of cells, and for a fixed value of d, the number of notches can be approximated as a binomial random variable.

We will now look at several different multicarrier CDMA schemes and for each, the number of narrowband users which can be present so that the CDMA users do not require an excessive amount of notching will be found. Later in this paper, the performance of the CDMA system employing the minimum mean-squared error (MMSE) receiver will be investigated. The sampling rate used in the MMSE is $1/MT_c$ or $1/T_c$ in the single-carrier case. The CDMA signals with spectrally efficient pulse shapes will typically be contained within the frequency range $(-1/MT_c < f < 1/MT_c)$. However, the notching can really only be done uniquely within the range $(-0.5/MT_c < f < 0.5/MT_c)$ as a result of the sampling rate and the corresponding aliasing. Each notch within this range, therefore, gives rise to a second notch outside of this range, but still within the range $(-1/MT_c < f < 1/MT_c)$. Thus, recalling that the BPSK and CDMA systems have the same data rate, there are only 16 unique notching locations for the single-carrier system with a processing gain of 32 chips/bit. In a general multicarrier system with M carriers, the spectrum occupied by the signal on each carrier will have $16/M$ unique notching locations.

We now establish a criterion to determine the limit on how many narrowband users can occupy the channel as a function of the notching threshold T. For a given carrier, it will be declared that if more than half its unique frequency slots must be notched, then that carrier will not be used. For systems with $M = 1, 2$, or 4 carriers, there are 16, eight, and four unique frequency slots, respectively, on each carrier, so a carrier will be dropped if there are more than eight, four, and two unique notches required.

It is quite possible that under this criterion, a user may need to drop some of its carriers while other carriers remain operational. For a large number of carriers, if only a few of them are not used, the system may experience a performance loss which is tolerable. We call on some results, which will be explained in detail in Section V, to declare for our purposes here in this section that if 3/4 of the carriers remain, then the system can still function adequately. Combining this with the previous criterion for dropping a carrier, the complete criterion for determining how many narrowband users can be supported for a given value of T is that a CDMA user will be dropped if it must drop more than 1/4 of its carriers. For systems with $M = 1, 2$, or 4 carriers, the system must retain at least one, two, or three of its carriers.

Using the notching probability plots in Fig. 3, results were found by generating a random location for a CDMA user and determining how many notches it would require and hence how many of its carriers would remain. The density of narrowband users/cell for which this criterion can be satisfied

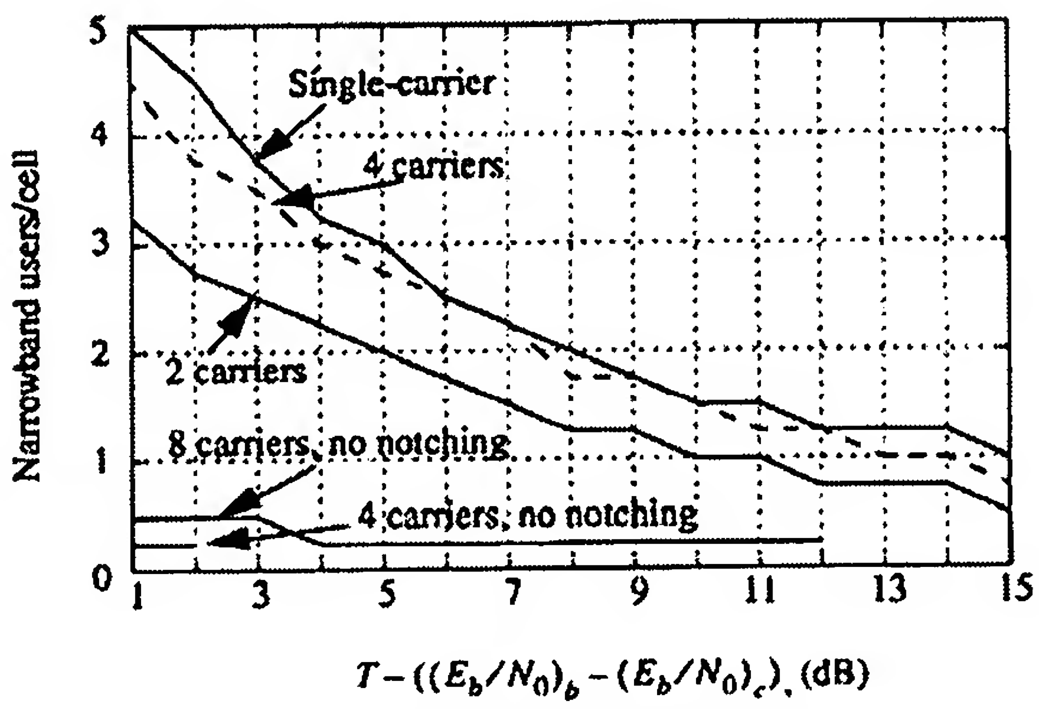

Fig. 4. Narrowband users/cell tolerable to CDMA system before too much notching is required. Shown are single-carrier and multicarrier cases. The "no-notching" curves represent cases in which a carrier is dropped if even one notch is necessary.

was found for a range of values of $T-((E_b/N_0)_b-(E_b/N_0)_c)$ in dB, and the results appear in Fig. 4, for $M = 1, 2$, or 4 carriers. Notice as expected, that as T gets larger, and hence more notching is necessary, fewer narrowband users can be present. Also, as $(E_b/N_0)_b-(E_b/N_0)_c$ gets larger, the CDMA users are less likely to need notches, and more narrowband users can be present.

It has been suggested previously that with the use of multicarrier CDMA, it is possible to avoid the narrowband users in an overlay scenario by simply not transmitting on those carriers which might interfere with a narrowband user [1]. This possibility was also examined here for comparison. We will first modify the previous notching criterion and declare that if the CDMA signal on a given carrier is received at a high enough power level in terms of the notching threshold T, the carrier will not be used, as opposed to simply placing a notch in the previous scenarios.

We will consider both four and eight carriers in this type of system. It does not seem fruitful to raise the number of carriers beyond eight with a composite processing gain of 32 chips/bit for several reasons. First, even assuming that the CDMA signals on each carrier would experience independent fading, the incremental diversity advantage realized by using more carriers diminishes with such a high number of carriers. Second, it has been assumed that the CDMA system, when used with multiple carriers, can be split such that transmission takes place in disjoint frequency bands with sufficient frequency separation. Considering issues related to spectrum allocation, this might be plausible with two or even four carriers, but the possibility becomes less likely with a large number of carriers. Finally, the process of tracking the fading processes, which is not considered in this paper, would become tremendously complex with so many carriers.

As shown in Fig. 4, for four and eight carriers, the number of narrowband users tolerable to the CDMA system falls far below the performance of the systems which use notching. The presence of a reasonable amount of narrowband users would simply require that too many carriers be dropped. This suggests strongly that the hybrid system previously described—that is, the system which uses notching and will drop a carrier if it requires excessive notching should be used. Again, this must be tested in terms of the effect on CDMA performance, which will be done in Section V.

In Fig. 5, a combination of the results of Figs. 2 and 4 are shown. Several two-dimensional (2-D) capacity curves, each with a constant value of $(E_b/N_0)_b-(E_b/N_0)_c$, were formed by finding the tolerable densities of CDMA users/cell from Fig. 2 and narrowband users/cell from Fig. 4 for a given value of the notching threshold T. This was repeated for a range of values of T. As $(E_b/N_0)_b-(E_b/N_0)_c$ gets larger, the CDMA users are less likely to interfere with the BPSK user and are less likely to require notches, and thus more users of each type should be supportable.

It is important to keep in mind that we have not yet considered how much self-interference the CDMA system can handle, nor the effects of narrowband interference and notching on CDMA performance. We have only considered two things, which nonetheless do impose some limitations on user capacity: 1) the number of CDMA users for which the narrowband system's performance is severely degraded according to the criterion described in Section III and 2) the number of narrowband users for which the CDMA users would simply require too much notching. In the next section, we will look at the CDMA performance in more detail.

V. System Simulations and Results

In the previous two sections, some broad capacity limits were found for both the CDMA and the narrowband systems, imposed by the notching. In this section, the capacity limits of multicarrier CDMA will be examined further. Results from Sections III and IV will be extended to include the effects on CDMA performance of multi-access interference (MAI), narrowband interference (NBI), notching, and the possibility of operating on fewer carriers than the maximum.

We consider the use of the MMSE receiver, which is well-suited to the overlay environment. It has been shown to reject MAI [6]–[8], NBI [9], [10], and intersymbol interference (ISI) [4]. It also has the desirable property that it can adapt to a filtered code sequence without even knowing that the code has been filtered [4]. In [11], it was shown that the MMSE can successfully realize diversity in a frequency-selective fading channel and that there is a substantial performance loss when all of the paths of all of the interfering users are not tracked explicitly in forming the Wiener solution. The performance of the MMSE was evaluated in the multicarrier case in [12], where it was reaffirmed that all of the paths of all of the CDMA users must be tracked in order to avoid a sizable performance loss.

The performance in the overlay environment is a relatively straightforward extension of the analyzes given in [11] and [12]. Some slight modifications are that the desired CDMA user now may operate with a filtered code sequence, and narrowband noise must be added when necessary. We consider the general multicarrier system described earlier, with M carriers and a processing gain per path of N/M.

It is also assumed that the desired user's code sequence in the mth carrier will be filtered (when necessary) using the

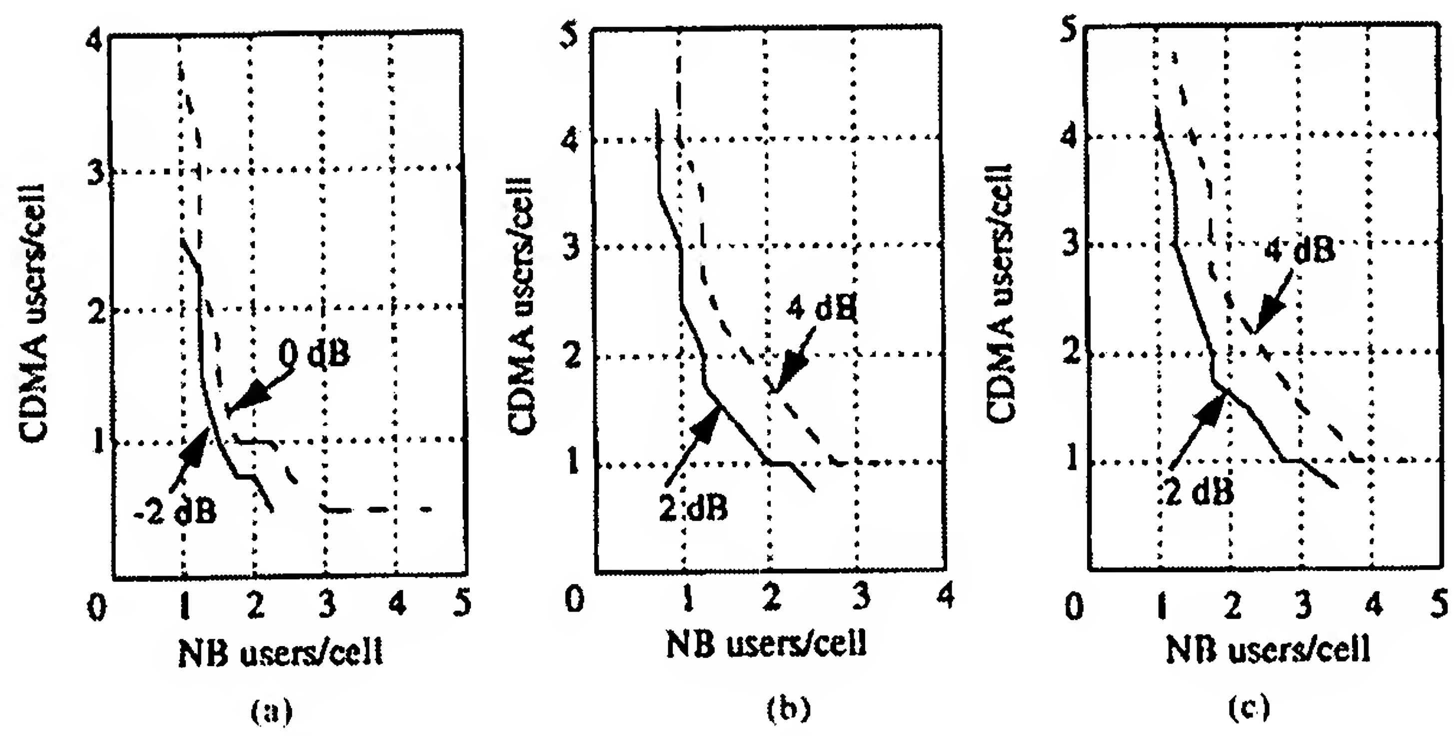

Fig. 5. Two-dimensional (2-D) capacity curves combining Figs. 2 and 4. Labels on curves indicate the value of $((E_b/N_0)_b - (E_b/N_0)_c)$. Processing gain is 32 chips/bit. (a) Single-carrier case. (b) Two-carrier case. (c) Four-carrier case.

DFT-based filtering method from [4], zero-padded to 8 bits, which results in a code sequence of length greater than the processing gain, N/M in this case. If L bits of zero-padding are used in performing the filtering, then the filtered sequence can be expressed as the cascade of L individual sequences of length N/M, as $\mathbf{c}_{1,m} = \mathbf{c}_{1,m,-L/2}, \ldots, \mathbf{c}_{1,m,0} \cdots, \mathbf{c}_{1,m,L/2}$, with $\mathbf{c}_{1,m,0}$ in the middle associated with the desired signal component and the other sequences corresponding to ISI. Note that on each carrier, the filtered code sequence will be different as the notching necessary on each carrier is generally not the same.

For the mth carrier, the samples of a chip-matched-filter bank will be collected during the ith bit interval, resulting in a column-vector of N/M samples given by

$$\begin{aligned}\mathbf{r}_m(i) = {} & \gamma_{1,m}(i)d_1(i)\mathbf{c}_{1,m,0} + \mathbf{n}_m(i) + \mathbf{j}_m(i) \\ & + \sum_{\substack{n=-L/2 \\ n\neq 0}}^{n=L/2} \gamma_{1,m}(i)d_1(i-n)\mathbf{c}_{1,m,n} \\ & + \sum_{k=2}^{K}\sqrt{\left(\frac{P_k}{P_1}\right)}\gamma_{k,m}(i)[d_k(i)\mathbf{f}_{k,m} + d_k(i-1)\mathbf{g}_{k,m}]\end{aligned} \tag{5}$$

where $\gamma_{k,m}(i)$ is the fading process on the mth carrier of the kth user during the ith bit interval, and the fading processes for the same user on each carrier are independent. Also, $\mathbf{f}_{k,m}$ and $\mathbf{g}_{k,m}$ are the even and odd cyclic shifts of the kth user's code sequence on the mth carrier, and $\mathbf{n}_m(i)$ is a vector of length N/M of independent complex Gaussian noise samples, with the real and imaginary parts each having variance of $\sigma^2 = 2E_b/N_0$. The vector $\mathbf{j}_m(i)$ consists of the sum of samples of all of the narrowband noise processes present in the mth carrier, if any. Each process is complex, with the real and imaginary parts independent, and each with a correlation matrix of the form

$$\begin{aligned}\mathbf{R}_{J,J}(i_1, i_2) = M\left(\frac{P_b}{P_c}\right)\mathrm{Sa}\left(\frac{2\pi(i_1 - i_2)}{N/M}\right) \\ \cdot\cos(MT_c\Delta\omega(i_1 - i_2))\end{aligned} \tag{6}$$

for the (i_1, i_2)th element, where (P_b/P_c) is the narrowband-to-CDMA near-far ratio, $\mathrm{Sa}(x) = \sin(x)/x$, and $\Delta\omega$ is the frequency difference between the location of the narrowband user and the CDMA carrier frequency. The remaining quantities in (5) were defined in Section II.

It was shown in [12] that the receiver will work best if the M different received vectors of (5) are cascaded into a single composite vector of length N, given by

$$r(i) = \left(\mathbf{r}_1^T(i), \mathbf{r}_2^T(i), \ldots, \mathbf{r}_M^T(i)\right)^T \tag{7}$$

and a single Wiener filter is formed, given by $\mathbf{w}(i) = \mathbf{R}^{-1}(i)\mathbf{p}(i)$, with $\mathbf{R}(i)$ and $\mathbf{p}(i)$ the correlation matrix and steering vector, given by

$$\mathbf{R}(i) = \begin{bmatrix}\mathbf{R}_{1,1}(i) & \mathbf{R}_{1,2}(i) & \ldots & \mathbf{R}_{1,M}(i) \\ \mathbf{R}_{2,1}(i) & \mathbf{R}_{2,2}(i) & \ldots & \mathbf{R}_{2,M}(i) \\ \vdots & \vdots & & \vdots \\ \mathbf{R}_{M,1}(i) & \mathbf{R}_{M,2}(i) & \ldots & \mathbf{R}_{M,M}(i)\end{bmatrix}$$
$$\mathbf{R}_{p,q}(i) = E\left[\mathbf{r}_p(i)\mathbf{r}_q^H(i)\right] \tag{8}$$

and

$$\mathbf{p}(i) = \begin{bmatrix}\mathbf{p}_1(i) \\ \mathbf{p}_2(i) \\ \vdots \\ \mathbf{p}_M(i)\end{bmatrix} = \begin{bmatrix}E[d_1(i)\mathbf{r}_1(i)] \\ E[d_2(i)\mathbf{r}_2(i)] \\ \vdots \\ E[d_M(i)\mathbf{r}_M(i)]\end{bmatrix}. \tag{9}$$

The bit decision is then made as $\hat{d}_1(i) = \mathrm{sign}(\mathrm{Re}[\mathbf{w}^H(i)\mathbf{r}(i)])$ for coherent combining of the paths. It makes sense to use coherent combining in this case because it was previously stated that all of the fading paths of all of the users should be tracked anyway in order to avoid a large performance loss. The task of tracking the fading processes in a dynamic environment is currently an area of active research.

If the received vector on the mth path is rewritten as $\mathbf{r}_m(i) = d_1(i)\mathbf{p}_m(i) + \tilde{\mathbf{r}}_m(i)$ where $\tilde{\mathbf{r}}_m(i)$ represents a composite interference process consisting of MAI, AWGN, NBI, and ISI, and the individual vectors on each carrier are cascaded to form a single vector $\tilde{\mathbf{r}}(i)$, it can be shown with the matrix-inversion lemma and a Gaussian approximation on the composite interference that the probability of error using

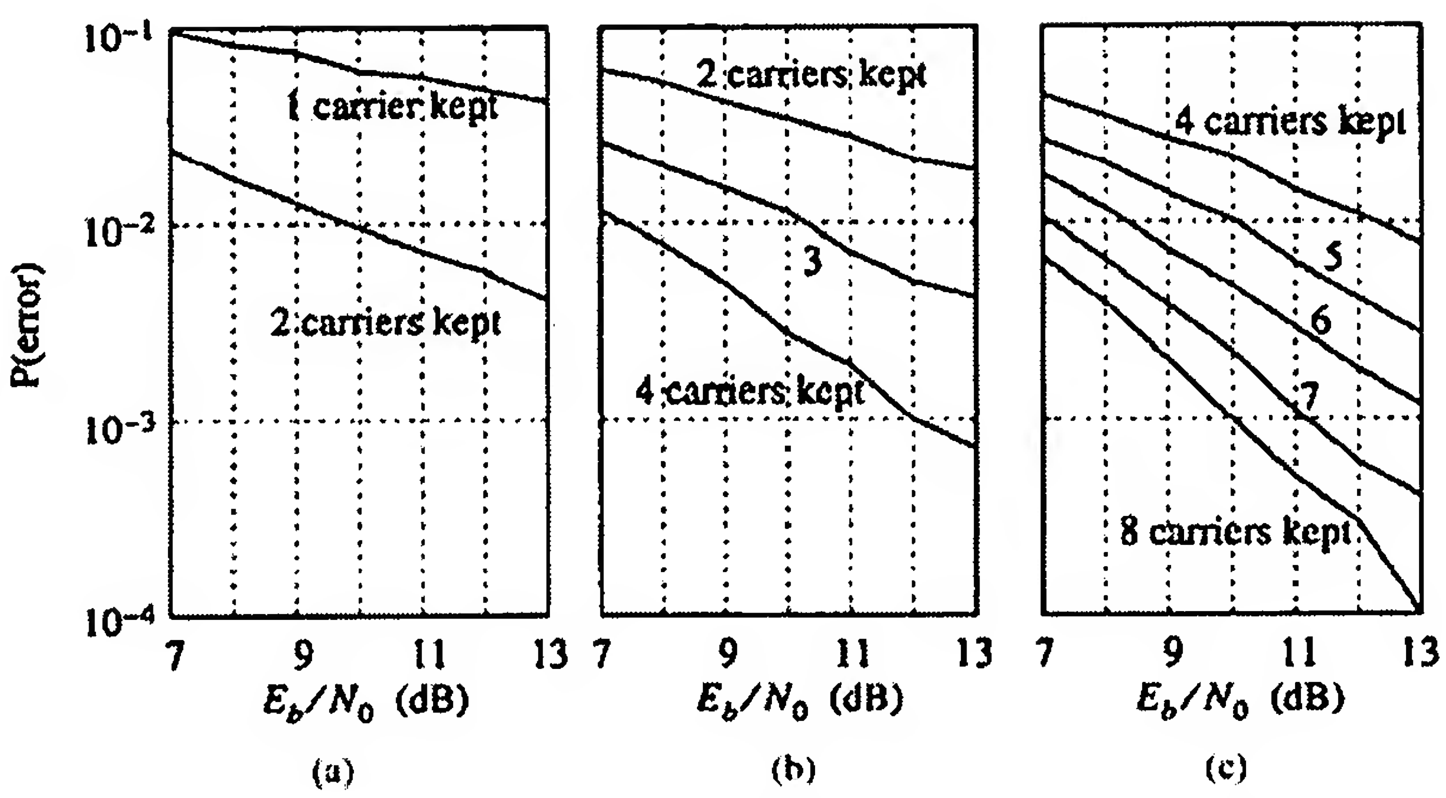

Fig. 6. Probability of bit error for multicarrier CDMA system, with processing gain of 32 chips/bit and 3.0 CDMA users/cell and no overlay. Different curves represent performance when a number of the total carriers are kept. (a) Two carriers. (b) Four carriers. (c) Eight carriers.

coherent combining of the paths can be approximated by [11]

$$P_e \approx Q(\sqrt{2\mathbf{p}^H(i)\tilde{\mathbf{R}}^{-1}(i)\mathbf{p}(i)}) \qquad (10)$$

with $\tilde{\mathbf{R}}(i) = E[\tilde{\mathbf{r}}(i)\tilde{\mathbf{r}}^H(i)]$ the composite interference correlation matrix.

Before proceeding to the overlay simulations, a test of the multicarrier system was performed in the absence of overlay, in order to determine the effects of dropping one or more carriers. For a system with a fixed 3.0 CDMA users/cell and the previously described environment, the probability of bit error is shown in Fig. 6 for different multicarrier systems. In each, the number of carriers kept by the system is varied. It is seen that for the $M = 2$ carrier case, keeping just one carrier results in a large performance degradation. However, for $M = 4$ carriers, the degradation is not too severe if only one of the carriers is dropped. Likewise, for $M = 8$ carriers, if six of them remain, the degradation seems tolerable. Thus, the criterion described previously in Section IV was that a CDMA user must be dropped if less than 3/4 of its carriers remain after the necessary notching is performed.

The performance of the CDMA system using an MMSE detector was then simulated, with the overlay environment described in Section II. For a given density of narrowband users/cell, the corresponding density of CDMA users/cell that could be simultaneously supported by the channel was found. The value of $(E_b/N_0)_c$ used is important here. According to the capacity constraints examined in Sections III and IV, it is clearly best that the CDMA system operate at a low value of $(E_b/N_0)_c$, as its effects on the narrowband system are reduced without requiring an excessive amount of notching. In this section, however, we are interested in the BER of the CDMA system, for which it is obviously desirable that higher values of $(E_b/N_0)_c$ be used. A capacity criterion imposed to take into account the CDMA performance is that a BER of 0.01 is desired, as it was for the BPSK system. This criterion will be used in conjunction with the capacity limits described in Sections III and IV.

In order to combine these results with those of Sections III and IV, the notching threshold T and the value of $(E_b/N_0)_b - (E_b/N_0)_c$ must be chosen so as to satisfy the capacity curves

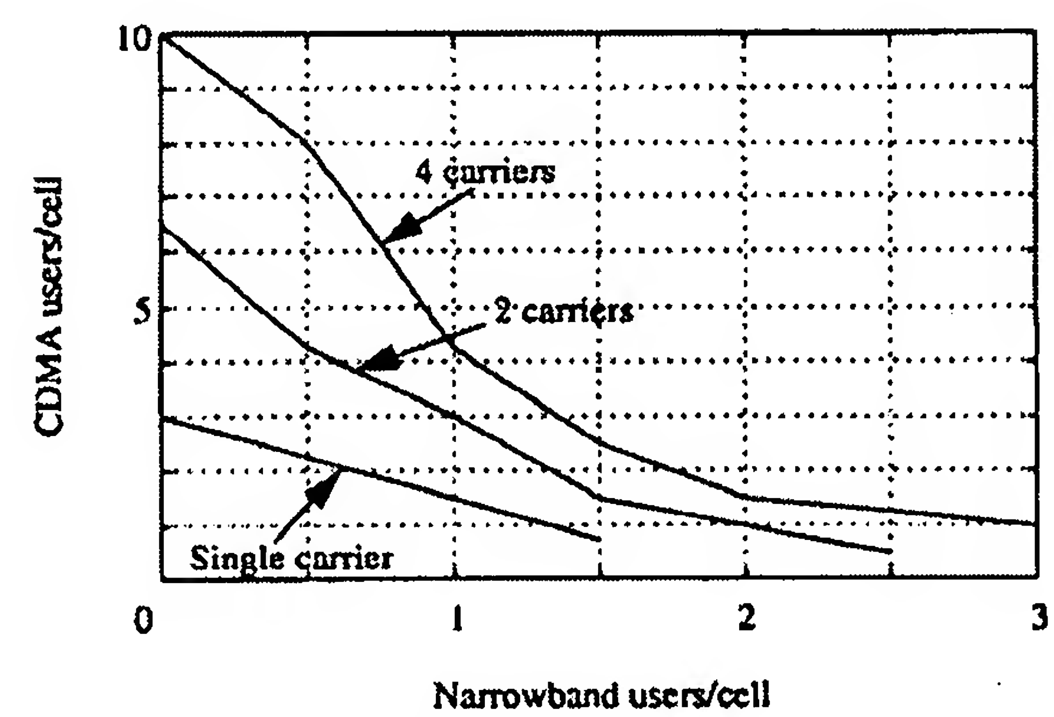

Fig. 7. Two-dimensional capacity curves for multicarrier CDMA, taking into account both CDMA receiver performance and results from Fig. 5. Processing gain is 32 chips/bit.

shown in Fig. 5. In Fig. 7, the results of combining the criterion just described, that is an average BER of 0.01 for the CDMA user, with the results of Sections III and IV, are shown.

In these results, the value of $(E_b/N_0)_c$ was chosen to be 17 dB in the single-carrier case, while a value of 13 dB was ideal for the two-carrier and four-carrier cases. Recall that in the multicarrier scenarios, a smaller value of $(E_b/N_0)_c$ could be used in order to achieve the same performance in terms of CDMA reception. This in turn allows the limits of Sections III and IV to be relaxed in comparison to the single-carrier case.

When there is no overlay, i.e. no narrowband users present, the CDMA system can be loaded to three, 6.5, and ten users/cell for one, two, and four carriers. The number of CDMA users/cell that can be supported decreases quite rapidly as the number of narrowband users/cell is increased for all three of the curves shown. In fact, there is about a 50% reduction in CDMA capacity in comparing a system with one narrowband user/cell and a system with no overlay. There is a noticeable improvement in capacity over the single-carrier case when two carriers are used and an additional increase when four carriers are used. A two-carrier system can support roughly twice the number of CDMA users as can the single-carrier system, and the four-carrier system, in turn, can support about twice what the two-carrier system can support.

VI. Conclusion

In this paper, the performance of a cellular overlay system with a fading channel model was evaluated. The effects of the CDMA system on the narrowband system were quantified, and the effects of notch-filtering were found to be beneficial. It was found that the use of multiple carriers allows the CDMA users to transmit less power than in the single-carrier case, and thus more users can be supported without causing interference to the narrowband system. It was also found that a multicarrier CDMA system which avoids narrowband users by notching outperforms a system which simply drops any carrier which interferes too much with a narrowband user. The possibilities for CDMA overlay for use as a long-term transition from narrowband cellular to CDMA cellular are strongly argued by the results of this paper.

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